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UK Primary Steelmaking Review 2025

CONTENTS

EXECUTIVE SUMMARY

This independent review, commissioned on behalf of the Secretary of State for Business and Trade and the Minister of State for Industry in January 2025, with the support of the UK Steel Council, considers the United Kingdom's requirements and options for domestic primary iron production from iron ore, to supplement electric arc steel recycling in the 2020s and 2030s.

The UK's steel consumption is in the order of 12 million tonnes per year (Mtpa) with potential to rise to almost 15 Mtpa with the expansion of new renewable energy infrastructure (1). Domestic production of steel currently meets less than 30% of that demand, from Blast Furnaces or Electric Arc Furnaces (EAF) and is assumed in this report to be undergoing a transformation, with all melting capability expected to move to EAF and all remaining Blast Furnace primary ironmaking assets to be decommissioned [unconfirmed at time of publication]. This 5-fold expansion of EAF steelmaking will benefit from the UK's current surplus supply of steel scrap, recycling it domestically to produce up to 6Mtpa of lower embodied carbon steel products by 2028 for the domestic and export markets.

Analysis of the expected product mix shows that steelmakers collectively will also have an immediate requirement for around 1 Mtpa of 'primary iron', that is, iron derived from virgin iron ore, to blend with the scrap and other alloying elements across a range of higher performance products. This may rise to 2-3 Mtpa in the 2030s. It is of note that iron was added to the UK Critical Minerals list in 2024 (2).

Whilst this need can be met initially from offshore supplies of blast furnace pig iron or directly reduced iron (DRI), in order to meet lower emissions commitments and compete with rapidly decarbonising international markets, this primary iron should aim to be supplied from DRI or similar reactors, utilising natural gas and with a transition to low emission hydrogen DRI, as soon as economics allow. This emergence of EAF + scrap + DRI is in line with the majority of current US steelmaking capability and with all major steelmaking transformation investments currently announced across Europe during the early 2020s, where captive DRI capability is being added to replace Blast Furnaces and/or to supplement the growing competition for quality scrap.

Depending on the scale of domestic production targets and sovereign capability targets the UK may therefore require between 1-3 Mt of iron reduction capability. Should this be required onshore, a decision largely reliant on energy pricing for its economic competitiveness, this would likely represent a single facility with a total capex cost of £1-3Bn, supported by fossil-free electrical and hydrogen generation infrastructure. Should this option be preferable a detailed study is recommended in support of investment decisions in the near future, and/or an accelerated programme of domestic support for modular distributed ironmaking options. The alternative to domestic production is that the UK relies on the emerging international markets for green iron products to supplement scrap steel recycling, an option which has the potential in future to optimise global supply chain efficiencies and net CO_2 emissions by relocating ironmaking to geographical areas where iron ore supply and low cost renewable energy overlap, but which also has dependency and sovereignty implications.

In either case an integrated plan for 'scrap plus primary iron' (and other critical metal alloying additions) is recommended, supported by R&D for grade transitions, along with close monitoring and support for further technological developments in ironmaking.

Materials Processing Institute, November 2025

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MATERIALS PROCESSING INSTITUTE
UK PRIMARY STEELMAKING REVIEW 2025

TERMS OF REFERENCE AND APPROACH TO THE REVIEW

Terms of Reference (January 2025)

Output: Produce a clear recommendation on the viability of technologies for the production of primary steel in the UK.

"Review the viability of technologies for the production of primary steel, including Direct Reduced Iron. In this context, we mean production of primary steel using iron made in the UK from iron ore. This review will focus upon UK capability to derive iron from iron ore, to subsequently use in the steel making process"

An interim report was shared with DBT at the end of January 2025 in order to position its findings with other ongoing assessments; the final Review was submitted in March 2025 for integration with the broader Steel Strategy, for which a Green Paper had been on 16th February 2025.

Subsequent feedback, developments and revisions have been incorporated in this version for public release in November 2025.

Approach

An expert assessment of the techno-economic issues was supported by discussions held in confidence with steelmakers and supply chain actors, particularly including organisational members of the UK Steel Council (Convened by the Secretary of State for Business and Trade on 7th January 2025)

1. **For Section 1 – Demand:**

   Development of relevant scenarios requiring primary steel capability

   In order to develop these, the authors considered:

   - The current range of steel product types in demand in the UK economy or from UK producers
   - The potential future demand profile
   - The requirements across that demand, for primary iron that would be needed to blend with recycled steel in order to produce new steel of the necessary quality and carbon footprint.

2. **For Section 2 – Production**

   - Essential steelmaking considerations when transitioning from coal-based to Electric Arc Furnace steelmaking and assessing any ongoing need for primary iron inputs.
   - Assessment of global developments and investments in commercial 'green' iron and steel making, i.e. routes to finished steel products which emit significantly lower CO_2 per tonne of product than the current average.
     - Reasons for and implications of investments
     - CapEx and OpEx estimates for low net emission iron production
     - Infrastructure requirements – e.g electrical supply, hydrogen generation or supply, iron ore processing, transport links, site footprint.

3. **For Section 3 – Supply**
   - Assessment of associated developments in the primary iron supply chain, i.e. the changing quality of available ores, scaleup of green hydrogen, and the evolution of potential 'Green Iron Corridors' as ore suppliers' business models move to green iron production.
   - Assessment of related supply chain impacts of choices in ironmaking – e.g. value chain for steelmaking slags, utilisation of wastes.

Note: Assumptions are made in this report based on British Steel's announcements before the UK Government's April 2025 intervention and the passing of the Steel Industry (Special Measures) Act 2025, about an intention to transition from blast furnaces to electric arc furnaces. At the time of publication no final decisions or details of this transition had been made public by British Steel.

GLOSSARY

BF	Blast furnace – currently the dominant method worldwide for converting iron ore to molten iron by reacting with fossil carbon (coke, made from coal) and fossil limestone. Economically efficient at consistent large volumes with a well-maintained plant, highest carbon emissions per tonne of steel of any major process
BOF	Basic Oxygen Furnace – molten iron (generally from a blast furnace) is reacted with oxygen to oxidise and remove impurities (as slag) and carbon (as CO/CO_2) and to convert the iron to steel.
CBAM	Carbon Border Adjustment Mechanism – incoming EU framework with a UK equivalent, which taxes the embodied carbon content in specified imports (including steel) in order to create a more level competition for domestic, lower emission producers
CC[U]S	Carbon Capture [Utilisation] and Storage – removal of CO_2 gas from emissions by a variety of technologies, utilisation of it (eg to create new chemical precursors) and/or permanent storage of it (generally by pressurisation and pumping into depleted fossil fuel aquifers)
Crude Steel	Steel as it is poured from a furnace (liquid steel), or the first solid cast product after the furnace. Use of this stage of production as a boundary makes comparison between steelmaking process routes easier, especially since they tend to share very similar processes for casting and forming downstream of the furnace.
DRI	Direct Reduced Iron, A porous solid iron product made by reacting natural gas or hydrogen with iron ore (iron oxide) at between 650-950°C to reduce it directly to metallic iron. CO_2 emissions from the predominant natural gas furnaces are less than half that of a blast furnace; close to zero if renewably generated 'green' hydrogen is used. Dominant technology is fed with pelletised iron ore, reducing it to pellets of DRI, which look like small marbles, though some technologies avoid the pelletisation step by reducing powdered ore in a fluidised bed. Not as dense as solid iron because of the porosity created by removing the oxygen from the solid ore. For this reason, it can also be categorised as sponge iron.
EAF	Electric Arc Furnace. Melts metal with electrical energy which creates an extremely hot arcing current between (graphite) electrodes
ESF	Electric Smelting Furnace – aka Open Bath Steel Furnace (OBSF), Reducing Electric Furnace (REF). A continuously fed electrical melting unit which also uses electrical energy and/or carbon additions to complete the reduction and melting of the metal in question. In commercial use for ferroalloys (e.g ferrosilicon, ferromagnesium) but use in a 10x larger furnace for iron will not occur until 2027 at ThyssenKrupp in Germany. Potentially a more energy efficient melting and slag separation step for OBM's, which can feed hot metal directly to an EAF to blend with scrap. Able to use blast-furnace grade ore which is lower iron content and higher gangue content than DRI grade ore.

Gangue	Unwanted component of an ore – for iron ore, typically comprises oxides of silicon, aluminium, magnesium, calcium, phosphorous but varies ore to ore. Separates from iron in the large part once it is reduced and molten, as a floating slag
GPI	Granulated Pig Iron – molten iron from a blast furnace is quenched to form small pellets. Dense, relatively straightforward to handle and ship, melt easily in an EAF
H2DRI	Hydrogen DRI – emerging technology which substitutes natural gas with hydrogen in the same furnace. Often twinned with renewable energy-powered electrolysers to ensure a captive green hydrogen supply. (The authors are using H2DRI since some older literature uses 'HDRI' to refer to hot DRI)
HBI	Hot Briquetted Iron – DRI which has been compressed into a briquette while still hot from the reduction reactor. Densification improves storage, shipping conditions and subsequent melting
Hot Shortness	Hot shortness in steel is a tendency for steel to crack or become brittle when close to its melting point. This can cause problems in welded steels. Increased Copper levels in steel are known to cause hot shortness.
MBI	Melting base Iron, is a high purity, very low alloy content form of steel, typically with C contents of around 0.004%
NG-DRI	Natural Gas DRI, the dominant form in most of the world. Uses natural gas (methane) as the main supply to the reaction vessel to reduce iron ore
OBM	Ore-based metallics, a catch-all term for metal won from virgin ore – in this case, includes pig iron, sponge iron, DRI, HBI
Pig Iron	Iron created in a blast furnace, often cast into pig-shaped lumps if not being transferred directly to a steel furnace as hot metal
Rebar	Short for reinforcing or reinforcement bar, which is used in the construction industry to as a tension device added to concrete to form reinforced concrete and reinforced masonry structures to strengthen and aid the concrete under tension.
Scrap	Metal which has reached the end of its current use and is collected, screened and often crushed or shredded, in order to be recycled
Slag	Molten layer of oxides which are unwanted in the final product, which have separated from and are floating on top of the molten metal. Can have uses in cement making, aggregates and soil treatment.

SECTION 1 – DEMAND FOR STEEL AND DEMAND FOR PRIMARY IRON UNITS

1.1 Current UK demand for Steel products

The demand for ‘steel mill’ products in the UK is currently 7-8 million tonnes per year (Mtpa), across construction, power, transport, food packaging, engineering and defence. This has the potential to return to 10Mtpa by 2028 and potentially rise further to 12-14 Mtpa with the predicted year on year expansion of offshore wind power (1) and other government growth priorities.

UK Steel reports that in 2023 around 40% of this demand i.e. 3 Mt was met by steel produced (melted and poured) within the UK, falling below 30% in 2024, with the cessation of steelmaking in Port Talbot from October 2024 and conversion to re-rolling only until mid 2027, plus the reduced production through most other sites due to disadvantageous economics.

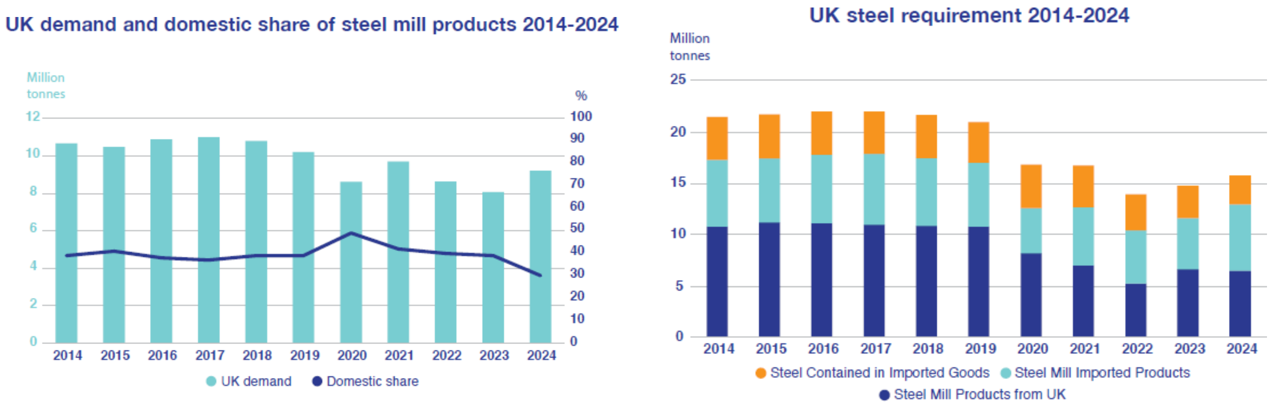


Figure 1: UK steel demand and domestic share 2014-2024

(source; UK Steel Key Statistics Guide 2024)

Imported finished goods

A further 7-8 Mt of steel also enters the UK each year as imported finished goods.

UK steel production – up to 40% of domestic demand before 2024

The major UK steel producers, i.e. those producing semi-finished ‘crude steel’ products from iron ore or melting recycled scrap, producing (slabs, plate, bar, coil) in the UK comprise:

- South Wales: Tata Steel UK (BF-BOF converting to EAF) producing flat products for construction, automotive and packaging, and 7 Steel UK (EAF) producing rebar for construction.
- Humberside: British Steel (BF-BOF expected to convert to EAF), producing long products for construction and infrastructure.
- South Yorkshire: (all EAF) Sheffield Forgemasters, Liberty Speciality Steels, and stainless steel producer Marcegaglia, serving more specialist markets.
- Downstream rolling mills, forming facilities, coating and finishing assets, and foundries remelting and casting ingots or finished iron and steel products are distributed across the UK economy.

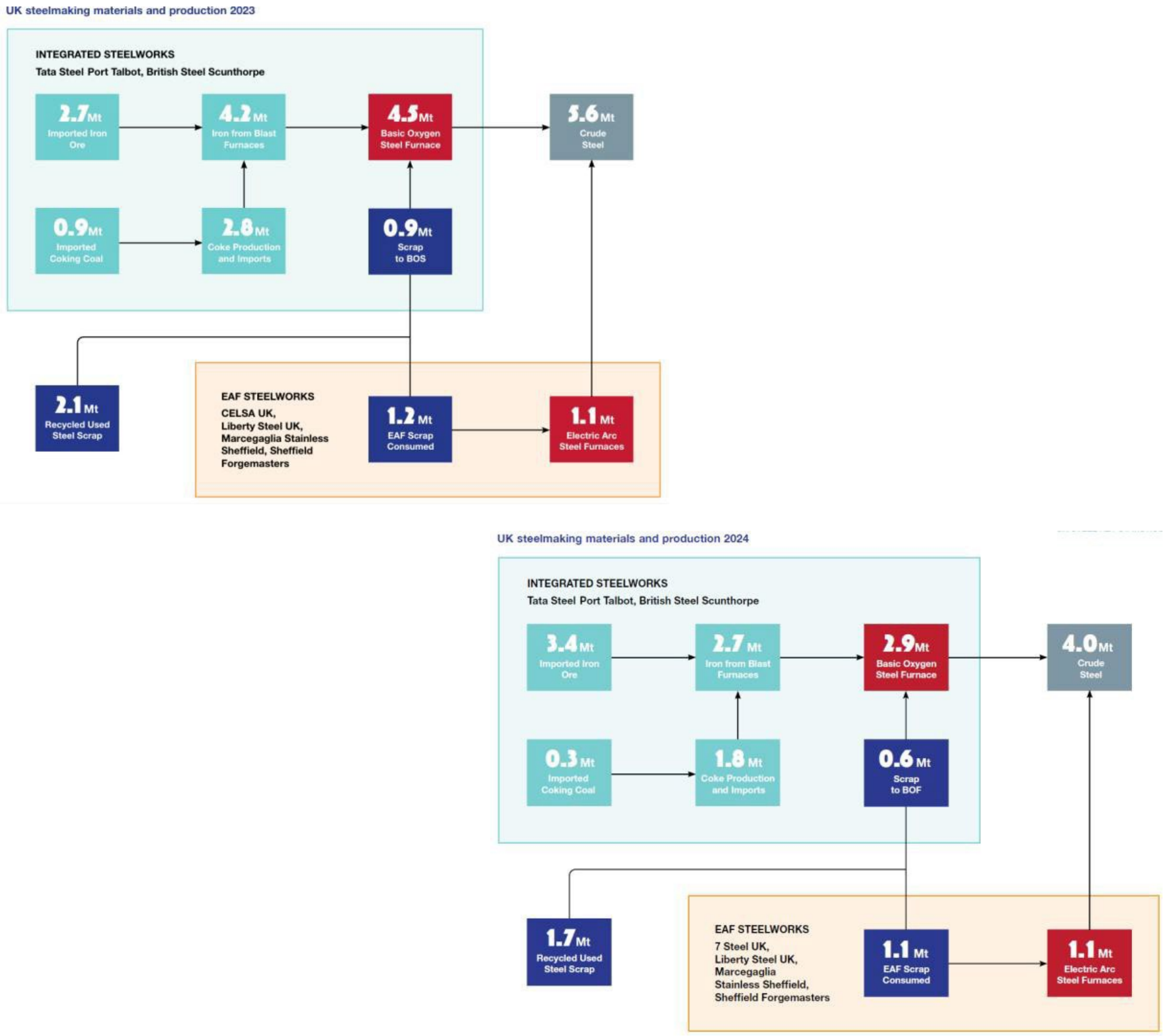


Figure 2: UK steelmaking (for domestic and export) and key materials flows in 2023-4

(source: UK Steel Key Statistics Guides 2024 and 2025)

Steel scrap and recycling

The UK is a mature economy which currently runs close to an even balance in terms of steel entering the economy from domestic production and imports, and steel being scrapped from its previous use. Annually, the recovery of scrap steel from end of life products, vehicles, buildings and infrastructure amounts to 10-11 Mt of which just over 2MT is recycled domestically and the remainder exported.

Due to an historic reliance on iron ore and relatively small EAF sector, the UK currently has a larger scrap surplus (domestic availability exceeding domestic demand) than most of its trading partners or competitors in similar economies around Europe and North America. The majority of the domestic scrap resource is currently exported to steelmakers in Europe with Spain and Turkey accounting for the largest markets. Steelmakers in the UK maintained a demand for around 2 Mtpa through to 2023, evenly split between electric arc furnace operators and BF-BOF plant operators, who already recycle up to 25% scrap steel through their process.

With the closure of Tata Steel's BF-BOF routes, reckoned to be the UK's largest single consumer of scrap steel during 2024, there is now a much lower demand for scrap within the UK, with Tata's order books for strip and coil products being fulfilled by re-rolling imported slab until the new EAF capacity is fully onstream.

The remaining demand for scrap will likely remain at 1.2-1.5 Mt during 2025-27 but will however increase several-fold starting in 2027 as new large (3Mtpa) EAF assets are brought onstream by Tata Steel (confirmed and supported by HMG co-investment) followed at some point by British Steel (based on previously published plans. No final decisions have been made at the time of publication)

The British Metals Recycling Association states 'we are more than able to meet future UK steel demand' from the existing scrap supply chain, a position which is corroborated by the UK steel scrap working group. Existing EAF operators expect to be able to continue sourcing scrap as they currently do – from factory returns and the bulk metals recycling sector – although some increase in price for cleaner grades is possible due to temporary supply constriction at the top end of the market while the domestic recycling sector reconfigures and invests to enable more stringent scrap sorting and quality guarantees.

Overview on Steel Grades

Steel grades and chemistries have developed over many decades to standardise the specifications for types of steel with required properties depending on their end use (e.g. strength, formability, wear resistance, corrosion resistance). From a steelmaking point of view these grades are defined by their metallurgy – i.e. their chemistry and microstructure. Chemistry derives from the raw materials and melting route to create the molten steel; microstructure from the interplay of chemistry and the thermo-mechanical processing steps (heating, cooling, rolling, forming) of the steel as it solidifies and is formed into finished or semi-finished products – coils, wire, strip, plate, beams etc.

Examples of steel grades that can be produced by both EAF and BOF (depending on specific requirements):

- Mild steel
- Low-alloy steels
- High-strength low-alloy steels (HSLA)
- Structural steel
- Reinforcing bar
- Some grades of stainless steel

Most standards specify the desired metallurgy, and physical properties of the steel rather than explicitly requiring a certain steelmaking route; some however (mainly in aerospace, nuclear and defence applications) explicitly prescribe a particular route of steel furnace and heat treatment. Part of the transition to new steelmaking routes will therefore require programmes of re-approval and/or updates to customer standards.

Steel grades can be divided into types based on chemical composition as follows. The first two categories are those with the most common need for ore-based metallics in their production

Steel Type	**Definition**	**Typical Uses**
Mild or low carbon steel	C below 0.3 %, no other alloying	Car body, pipes, construction, domestic appliances, beverage cans, melting base iron, cathode bar
Low alloy / high carbon steel	C_{eq}* below 0.9 %	Springs, wires, construction, rail steels, other long products, car bodies...
Alloy steels	C_{eq}* above 1 %	Car components, electric motors
Tool steel	Cr up 12%, Mo up to 5% W up to 18%	Tools, industrial tooling, drills, flanges, valves
Ferritic Stainless Steels	Alloyed with Cr and Ni	Domestic appliances, building cladding, sinks
Austenitic Stainless Steels	Alloyed with Cr and Ni	Utensils, food preparation food processing, piping, medical. Useful where materials cannot be magnetic
Duplex Stainless Steels	Alloyed with Cr, some Mo and Low C	Marine environments, chemical and liquid processing
Martensitic Stainless Steels	Alloyed with Cr, low Mo and High C	Kitchen utensils, knives, surgical instruments, turbine blades, bearings

The carbon equivalent, or C_{eq} is a way of combining the effects of alloying elements in terms of the equivalent amount of C addition. $C_{eq}* = C + Mn/6 + (Cr + Mo + V)/5 + (Ni + Cu)/15$

Table 1: Overview of steel types and uses

In terms of grades which are seen as extremely challenging to produce economically using scrap alone (due to background levels of unwanted elements, and/or nitrogen level requirements) the first category of carbon steels in Table 1 are the main ones of concern together with some specialist long product applications: **Section 2** deals with this issue in more depth.

Steel Type	Definition	Typical Uses	Need for primary iron content	% OBM for dilution and/or Nitrogen
Mild or low carbon steel	Carbon below 0.3 %, no other alloying	Car body, pipes, construction, domestic appliances, beverage cans Melting base iron, cathode bar	Car body Pipe (only deep sea) Plate Beverage cans White goods Specialist markets	35-40% variable 20-25% 35-40% 20-25% >50%
Some other low alloy carbon steels	Carbon up to 1%	High quality rails, Tyre cord.	Rail Automotive	25-50% >50%?

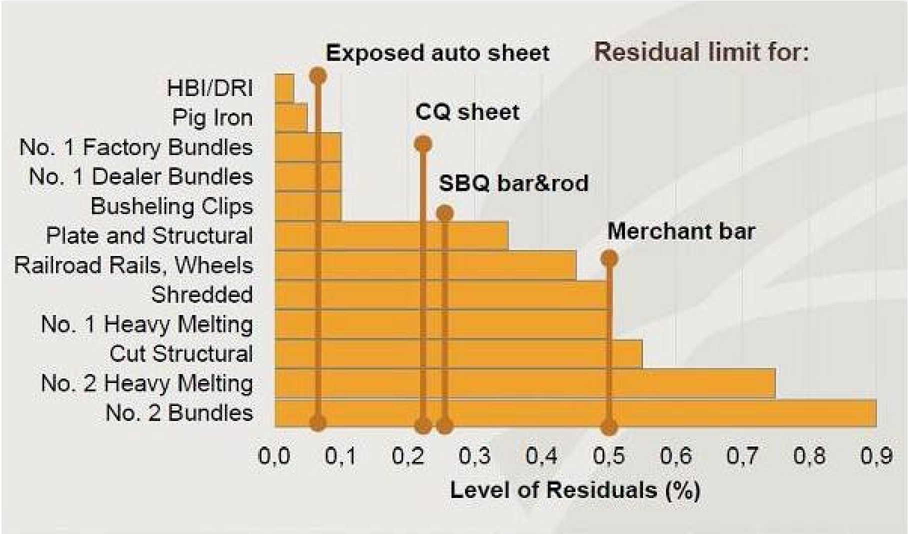
Table 1.1: Steel types from Table 1 where dilution of scrap with ore-based metallics (OBM) is commonly needed

Relationship of scrap quality, primary iron quality and final steel quality

The most significant factor in how much primary iron is needed to blend with scrap in order to reach a desired quality of steel is the correlating issue of the quality of scrap being used in the furnace.

This figure from a 2014 paper is often reproduced to explain the overlay of various scrap categories with the compositional tolerances of the products that can be made with them. In practice, commercial steelmakers use this type of data in ‘recipe’ models to calculate and procure the most economical blend of scrap types and primary iron units to hit the specification of their order books. Any scrap type being used in the recipe for a particular steel product for which it exceeds the residual tolerance (No. 2 Heavy Melting Scrap to make merchant bar for example) would therefore require dilution with a cleaner scrap grade or primary iron (HBI/DRI or Pig Iron) until the overall composition comes under the residual limit.

There is a further factor to consider when selecting to blend primary iron and scrap, which is control of dissolved **nitrogen** in the steel, an important criterion for products such as exposed auto sheet or beverage cans which must be rolled thin and formed.



Bulletin Events) “Latest Developments and Trends in the Global DRI/HBI Market”, Yuri Mishin
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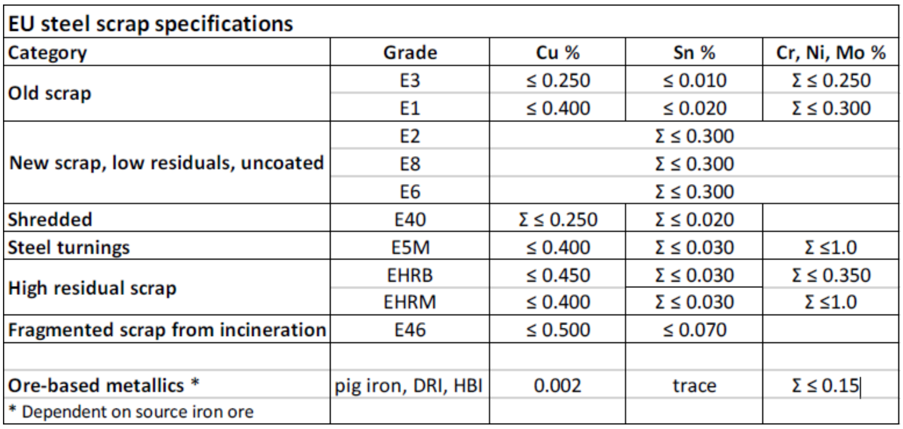


EU steel scrap specifications

Category	Grade	Cu %	Sn %	Cr, Ni, Mo %
Old scrap	E3	≤ 0.250	≤ 0.010	Σ ≤ 0.250
	E1	≤ 0.400	≤ 0.020	Σ ≤ 0.300
New scrap, low residuals, uncoated	E2	Σ ≤ 0.300		
	E8	Σ ≤ 0.300		
	E6	Σ ≤ 0.300		
Shredded	E40	Σ ≤ 0.250	Σ ≤ 0.020	
Steel turnings	E5M	≤ 0.400	Σ ≤ 0.030	Σ ≤1.0
High residual scrap	EHRB	≤ 0.450	Σ ≤ 0.030	Σ ≤ 0.350
	EHRM	≤ 0.400	Σ ≤ 0.030	Σ ≤1.0
Fragmented scrap from incineration	E46	≤ 0.500	≤ 0.070	
Ore-based metallics *	pig iron, DRI, HBI	0.002	trace	Σ ≤ 0.15
* Dependent on source iron ore				

Figure 3: Scrap quality vs steel grade residual limits

Innovation in high specification EAF steels

The art and science of producing low residual, low nitrogen steels through EAF routes is an ever-evolving field, supported by continual improvements in scrap segregation and sorting, and intelligent furnace control. Likewise there is work, particularly in Europe, into the development of new steel compositions plus heat treatments, which still perform well even with higher residual levels and may therefore be more suitable for producing deep drawing grades from high quality recycled steel feedstocks. However, much of this work is not yet at the point of commercial application. Researchers are developing ways to mitigate the effects of copper – e.g. specific heat treatment regimes with tighter control and lower temperatures to avoid the problem of hot shortness, or alloying with nickel to modify the behaviour of copper in the steel microstructure.

However, the detail of this innovation is beyond the scope of this review, which must consider current and near term needs and opportunities given best practice today in scrap control, electric melting, and primary iron production.

Even if residual levels of copper are within specification, it is a technical challenge to hit nitrogen levels required for deep-drawing steels when using the EAF route. The addition of carbon units into the melt, plus the adoption of a foaming slag practice (augmented by inert gas bottom stirring) will enable tap nitrogen levels to be lowered. The carbon required for the “carbon boil” can come from the injection of carbonaceous material (such as bio-char) or from carbon-bearing HBI, DRI or pig iron. Typical DRI carbon levels are shown in Appendix 3.

Increasing the percentage of direct reduced iron (DRI) in the electric arc furnace (EAF) charge mix improves steel quality by reducing the content of ‘tramp’ elements (such as copper, tin, nickel, chromium) and detrimental elements (such as phosphorous and sulphur) in the steel. Use of higher percentages of DRI also helps with nitrogen control both by dilution and from the slag foaming effect available from its carbon content (only true for natural gas or coke derived DRI, not H2-DRI which does not promote slag foaming) This results in higher purity steel with better mechanical properties, such as increased elongation, although yield strength and ultimate tensile strength may slightly decrease.

H2-DRI will however have zero dissolved carbon unless this is intentionally added (typically by bleeding methane/propane into the reductant gas mix at a small percentage to complete the reduction reaction, or by adding pulverised carbon to the charge DRI). This also results in H2-DRI having a higher melting point requiring additional melting energy and use of a larger hot heel of liquid steel which can impact productivity

Increasing the percentage of direct reduced iron (DRI) in the electric arc furnace (EAF) charge mix has several disadvantages, which are mainly attributable to the non-metallised content (gangue) compared to scrap:

1. **Higher Consumption:** It leads to increased consumption of electrical power, lime, fluxing materials, and carbon.
2. **Decreased Metallic Yield**: The metallic yield decreases as the DRI proportion increases.
3. **Increased Slag Weight**: The slag weight per ton of steel increases.
4. **Longer Processing Time:** The power-on time and tap-to-tap time of the EAF increase.

These factors can result in higher operational costs and reduced efficiency, particularly when slag prices are significantly lower than steel prices.

1.2 Future demand for Steel products

The UK has demand for a variety of steel products, including plate, rebar, and stainless steel. The UK's steel demand is driven by the construction and automotive sectors, as well as offshore wind projects.

Future steel demand by type

- **Plate**

  The UK's offshore wind aspirations will require between 20 and 25 million tonnes of heavy gauge plate steel between 2026 and 2050.

- **Rebar and tensioning strands**

  The UK will need almost 2.5 million tonnes of these products for construction

- **Stainless steel**

  The UK produces over 200,000 tonnes of stainless steel at its Sheffield plant, the majority of which is exported.

- **Finished steel**
  The automotive sector is a major consumer of finished steel, which can be produced locally or imported. Domestic demand has reduced in recent years

Future steel demand by sector

- **Construction**

  A major consumer of steel, accounting for 57% of the UK's total steel demand in 2017.

  This sector is the first to see significant migration of orders away from BF-BOS steel towards 'Green Steel' specifications

- **Automotive**

  A major consumer of steel, with opportunities to increase demand by growing the domestic supply chain.

- **Offshore wind**
  The UK's offshore wind pipeline will require a large amount of steel for components such as plate, rebar, and tensioning strands (UK CMIC Foresight report on Wind Turbines CR/24/009N)

- **Defence**
  Around 36,000 tonnes of steel was required in the 2022 to 2023 financial year for UK public procurement for defence and is expected to increase. This accounted for around 10% of total public procurement (by volume). Public procurement in 2024 accounted for around 450,000 tonnes, split between domestic and imported products.(Steel Public Procurement 2024 Steel Public Procurement 2024)

1.3 Need for primary iron in the production of certain steel grades

The transition to EAF based steelmaking presents different challenges in different market sectors:

Flat Products - thick	Can mainly be supplied from scrap chain
Flat products – thin	Most products will need 50% or more virgin iron
Long products – construction	Can be supplied from scrap supply chain
Specialist long products	Some products will need 25-50% virgin iron
Engineering and Special steels	Variable need for virgin iron
Stainless Steels	Adequately supplied by specialist scrap chain

Flat products - thick (typically 5mm – 50mm)
The majority of flat products in the form of plate for major infrastructure and other projects can be made via a fully scrap based EAF steelmaking process route.

Requirements on residuals can be achieved by good scrap control, requirements on nitrogen can be achieved by good furnace control. Use of additional process carbon would be mainly limited to the need for slag foaming and energy efficiency. Use of additional virgin iron units is unlikely to be needed. As for other construction sector products, improvement in the current capability in UK scrap sorting will be beneficial, but the technical capability exists to do this.

At the more stringent end of the plate steels market (e.g. Line pipe for sub-sea applications) there can be ultra-low requirements for combined levels of nitrogen, oxygen, phosphorus and sulphur. These will not be possible from scrap alone and will require a proportion of virgin iron units (possibly 25%-50% for these grades).

A significant and growing potential market has been noted for onshore and offshore wind power which might require 700-800kt of plate grade steel per year (20MT is estimated to be required in the next 20 years). With technical investment and good attention to scrap sorting, production of steels for this sector should be possible from UK scrap without significant need for additional iron units. The greater challenges for capability in this area lie in casting and plate rolling capability, which is old, in need of upgrading, and is fragmented across different companies.

Flat products – thin (typically 5mm and thinner)
There are bigger challenges in flat products sector for thinner gauge applications. In broad terms the technical challenge increases as the product thickness and need for high formability decrease.

At the less critical end of this sector, for white goods, panels, cladding, frames etc. the requirements for most steels can be made from UK scrap with little need for virgin iron units.

Thinner gauge products for sectors such as packaging where formability is an issue require stricter control of nitrogen and residual elements. These sectors will require a combination of very high quality scrap (e.g. the mooted ‘supershred’ grade) combined with up to 50% of virgin derived clean iron units.

Whilst not the primary purpose of this report, dedicated supply chains for these materials may need to be strengthened to ensure access to the right quality scrap rather than relying entirely on the higher quality scraps available on commercial market such as 4A bales: e.g. scrap off-take agreements with automotive and packaging supply chains. This process is already active at the high quality end of the market, via periodic auctions of manufacturers’ clean scrap supplies.

At the top end of this sector including highly formable exposed automotive sheet and 'DWI' (Drawn and Wall-Ironed) for beverage cans the challenge is much more stringent and a higher proportion of virgin iron units will be needed (>50%). There is experience by EAF steelmakers in the USA and elsewhere of making these steel qualities by the EAF route with quoted use of virgin iron between 50 % and 100%. More recent experience has suggested that these levels could be reduced.

There is a significant learning curve in developing the experience to make these grades after establishment of competence in EAF production for more standard grades. It is challenging to expect UK producers to supply this portion of the market (perhaps 200kt-300kt) in the period immediately following transition. If the aspiration is to retain market share then it might be necessary to continue to import cast substrate product and re-roll these grades in the interim period.

Long Products for Construction

The great majority of construction sector products (long products such as rebar, rod, structural sections, as well as flat products for panels, cladding and frameworks) can meet future requirements from a scrap-based product mix via EAF steelmaking. No significant problems are expected in supporting this market by electric arc steelmaking.

Some improvement in the current capability in UK recycling and scrap sorting will be beneficial. The technical capability exists to do this, given sufficient prioritisation and investment from suppliers and consumers.

In general, the requirements on residuals and nitrogen control can be achieved by good furnace control, meaning that the use of additional virgin iron units is unlikely to be needed. The use of additional process carbon would be mainly limited to the need for slag foaming and energy efficiency.

Specialist long products

Whilst most construction steels can be made from an entirely scrap-based process route there are a number of specialist products (total UK market size of up to 1Mt) where a combination of very high quality scrap and virgin iron units will be required.

The largest part of this market by volume is likely to be high quality rail steels (up to 0.5Mt/year). In this case there are significant requirements in terms of cleanness which will result in the need for high quality scrap with a proportion of dilution by virgin iron units (estimated at 25% to 50%)

Extremely high levels of steel cleanness (residual elements and nitrogen control) are required in products such as melting base iron (MBI) and cathode bar (each essentially pure iron), as well as ultra-thin products such as tyre cord. For these up to 100% virgin iron may be required as a starting material.

As noted in the preceding section, these more challenging products will require a period of familiarisation with operation of decarbonised steelmaking processes followed by development work to establish capability. It is likely, therefore that these steel qualities will not be made in the period immediately after transition.

There will also need to be a commercial judgement given the additional process steps, and associated time, as well as the increased cost of iron units on whether these remain cost competitive compared to imported competitor material produced via a non-decarbonised blast furnace route. It is in areas such as this where a simple CBAM type protection based only on carbon content but failing to account correctly for the higher processing requirement may not offer sufficient protections.

Engineering and specials steels (including aerospace and nuclear)

These steels are already traditionally made by the electric arc furnace route from scrap-based feedstock supplemented by significant additions of alloys to meet the required properties. Some of these steels have extremely strict requirements in terms of cleanness and compositional control, especially those for certain aerospace, nuclear and defence applications.

A significant difference between this market and the flat and long products noted above, is that for these products the markets are smaller, more specialised and demand a higher premium. It is therefore feasible to buy in more selective raw materials and alloys and to employ additional process steps such as vacuum arc remelting and electroslag refining to meet customer requirements.

Producers in this sector have established relationships with specialist recyclers and scrap suppliers and agreements with supply chains to take feedstock best suited to their products mix. There is little need for virgin iron units in this sector.

These producers consider that the current UK market will continue to be able to satisfy their needs even allowing for the increased scrap uptake of UK integrated steelmakers transitioning to scrap based melting.

Stainless steels

Like the engineering and special steels, these steels are already made by the electric arc furnace route from scrap-based feedstock supplemented by alloys to meet the required properties. There is little need for virgin iron units in this sector.

Producers have established relationships with specialist recyclers and scrap suppliers and agreements within manufacturing supply chains to take feedstock including stainless steel scrap designed to melt out as close as possible to their desired composition.

Producers consider that UK supplies of these recycled materials will continue to be able to satisfy their needs. The entry of UK integrated steelmakers transitioning to scrap based melting is unlikely to have significant impact on the market for stainless steel scrap.

1.4 Aggregated national demand for ore-based metallics (primary iron)

Conversations with individual steelmakers confirm an overall demand for primary iron units of up to 1MT by 2027-8 based on their current output plans, and at least 2-3 Mtpa in the event of domestic production fulfilling 80% of national demand, as national steel demand grows and stabilises around 14-15 Mtpa in the 2030's onwards and domestic scrap recycling hits maximum capacity. **Currently in the absence of new planned primary iron capability this would need to come from imports of DRI, HBI or pig iron, from international markets or from within the multinational groups with ownership of UK steelmakers.**

The variables that will affect the final demand for primary iron include market availability (and price) of steel scrap of sufficiently high quality - both from sorted shredded scrap ('supershred') and 'clean' scrap contracted as direct returns of consistent known quality from automotive forming lines, etc. A continued supply of clean scrap arisings is of course dependent on domestic production levels within any particular sector. For this reason the scrap supply profile and the ore-based metallics demand profile are coupled and dynamic, and dependent on forward investment and net carbon footprint requirements in the final steel products.

The anticipated demand for ore-based metallics (OBM) i.e. primary iron in 2027 onwards in response to the arrival of new capacity in EAF melting is therefore likely at first to be dictated solely by metallurgical needs (which range from zero OBM requirement for a large proportion of the grade mix, to 50% requirement for the most demanding thin strip products) rather than an overall shortfall of available affordable scrap steel sorted to the right quality. Current UK arisings of scrap are approximately 10 Mtpa although this may rise in the event of higher scrap process and/or an upturn in economic activity.

The exact *proportion* of OBM will depend on the grade mix being produced and the reality of the scrap quantities and qualities secured by the UK's steelmakers (particularly low copper scrap for thin strip products);

The exact *tonnage* will depend on maintenance or growth of the domestic market for UK steel products.

Table 2A below represents both factors in a straightforward model with an upper and lower demand scenario; **Tables 2B and 2C** display the same outcomes graphically. The model can be easily adapted to test and compare various hypotheses.

A summary based on current assumptions shows this demand adding up within the UK to at least 1Mtpa of ore-based metallics:

Scenario 1: production builds from 2027 to 7 Mtpa, and 100% EAF by 2030	**annual tonnage of steel**	**x**	**% of OBM required for steel quality**	**=**	**tonnage of OBM**	**tonnage of scrap**
Rebar	700,000	x	0%	=	**0**	700,000
Plate	750,000	x	10%	=	**75,000**	675,000
construction long products	1,000,000	x	15%	=	**150,000**	850,000
special forgings, aerospace	800,000	x	10%	=	**80,000**	720,000
specials - pipe, construction	800,000	x	25%	=	**200,000**	600,000
Hot rolled coil, standard	2,500,000	x	20%	=	**500,000**	2,000,000
Demanding hot rolled coil, packaging	300,000	x	50%	=	**150,000**	150,000
Total	6,850,000				**1,155,000**	5,695,000
(adjust for losses to slag, CO_2)	7,600,000		**Total**		**1,300,000**	**6,300,000**
Scenario 2 : 'UK Steel max' domestic supply 80% of a 15 Mt UK long term market						
Rebar	1,000,000	x	0%	=	**0**	1,000,000
Plate	1,500,000	x	10%	=	**150,000**	1,350,000
construction long products	2,000,000	x	15%	=	**300,000**	1,700,000
special forgings, aerospace	1,500,000	x	10%	=	**150,000**	1,350,000
specials - pipe, construction	1,500,000	x	25%	=	**375,000**	1,125,000
Hot rolled coil, standard	3,000,000	x	10%	=	**300,000**	2,700,000
Demanding hot rolled coil, packaging	400,000	x	50%	=	**200,000**	200,000
Future infrastructure growth (plate demand for wind)	1,000,000	x	15%	=	**150,000**	**850,000**
Total	11,900,000				**1,925,000**	**9,975,000**
(adjust for losses)	13,100,000		**Total**		**2,100,000**	**11,000,000**
OR: if maximum available scrap resource is 10MT					**3,100,000**	**10,000,000**

Table 2A: Estimated steel production tonnages and OBM requirements in the UK from 2027 and by 2035 with growth in both domestic demand and capacity growth

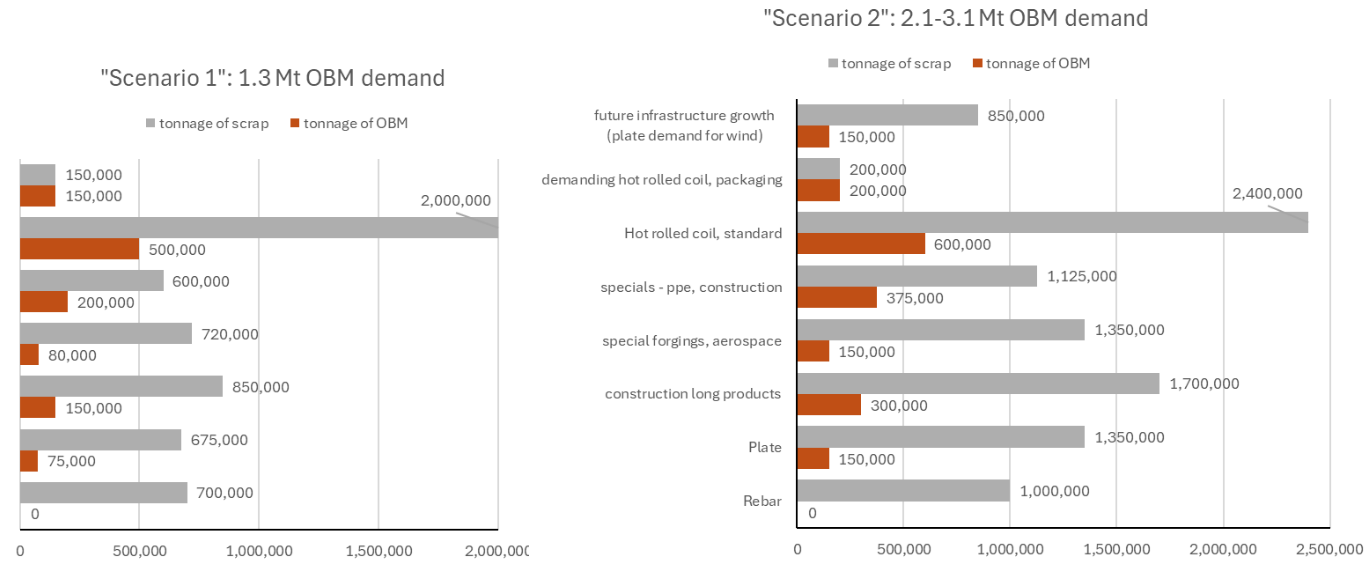


Table 2B: Individual Scrap and OBM demand forecasts by steel category

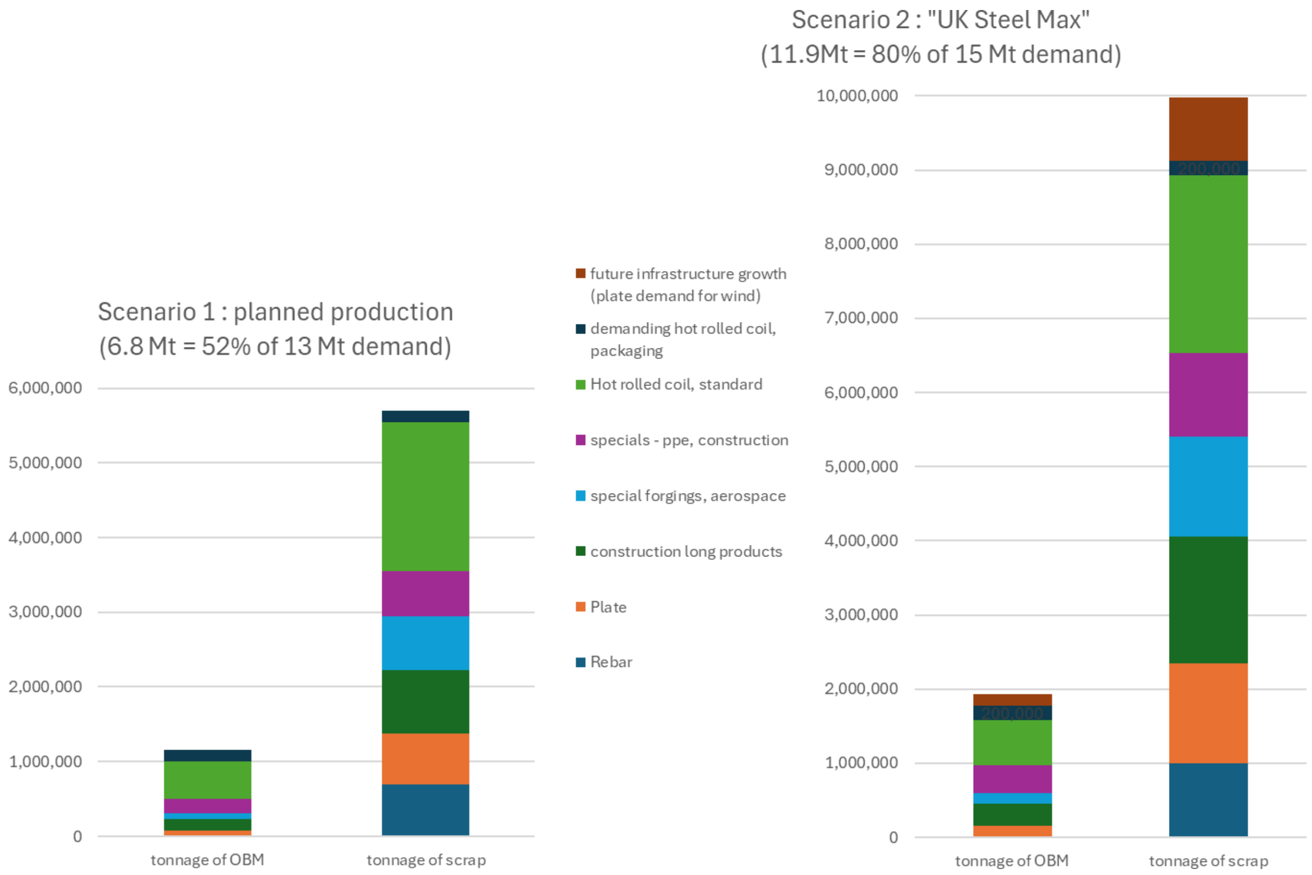


Table 2C: Aggregated Scrap and OBM demand forecasts, with breakdown by steel category

1.5 Use of Ore-based metallics (HBI, DRI and GPI) in the EAF

Accompanying the metallurgical suitability of OBM’s is the issue of familiarity and applicability of relevant steelmaking knowledge and experience.

HBI is a known quantity for UK steelmakers, having been imported and used for many years as supplementary iron units for BOF refining vessels as well as in EAF melting. It has a known and consistent chemistry, certified by analysis; a consistent shape and form enabling efficient material handling and storage, and its high density compared to scrap aids in keeping the charge bucket or conveyor load volumes and throughput times minimised.

DRI is commonly used in North America to blend with scrap to feed EAFs in mini mills (as is the compacted form, HBI), but is less familiar to UK steel makers; it is however the form in which the majority of new ironmaking capacity will be delivering iron to EAFs in the first wave of new European investments (see Section 2.1)

Pig iron is well understood in the UK steel industry since it is the solid form of the blast furnace hot metal used in BOF steelmaking; Granulated Pig Iron (GPI) is popular with many EAF steelmakers because of the ease with which it melts, and the high dissolved carbon content which reduces the need for additional carbon injection to clean the steel.

1.6 Grade Dependent Scrap-dilution Scenarios

The general approach is outlined above in Section 1.3 but each grade and furnace has its own detailed calculations in order to optimise the quality and price of its steel output, and the sophistication and reliability of these models and data sets grows year on year. Data analysis and modelling has been carried out by the authors on a range of grades and scrap qualities to determine the amount of dilution with ore based metallics (OBM) required so that the copper levels in the final product do not exceed the maximum specification.

Certain assumptions have to be been made, based on available data sets, particularly regarding the levels of copper in various grades of merchant scrap. The analytical composition of scrap metal is naturally variable, with uncertainties around the levels of residual elements in the steel. Also, by virtue of it being reclaimed from a variety of different sources and from different manufacturers/manufacturing routes, the specific analysis of a bundle of scrap will not be known. Improved sensors and upstream quality control will improve the confidence levels around KPIs on bundle to bundle variability.

Tables are available summarising the model predictions, but in the main, even with a detailed breakdown of grade requirements the general conclusions of the Review are corroborated – that there are few grades which cannot be made by a scrap-only practice, so long as the highest purity scrap is used. In practice, this type of scrap will become increasing scarce and more expensive, and so some calculations are made indicating OBM dilution rates necessary when using poorer quality scrap.

SECTION 2 – PRODUCTION

The authors collated relevant knowledge on steelmaking decarbonisation and EAF steelmaking in order to provide a steelmakers' perspective on the question of primary iron

We also conducted a review and assessment of global developments and investments in commercial 'green' iron and steel melting, ie routes to finished steel products which emit significantly lower CO_2 per tonne of product than the current average (1.8 tonnes CO_2 per tonne of liquid steel).

The additional 20-30% of CO_2 footprint which can be ascribed to a finished steel product due to downstream processing and transport, and mitigated through decarbonisation of reheating, rolling, coating etc was not within the scope of this review.

Section 2.1 Summarises the technical capabilities of EAF steelmaking in the context of the options for decarbonising steel supply, and outlines the key issues around carbon, nitrogen, and levels of unwanted non-iron residuals. Identifies technologies which are mid horizon options for the UK or still at earlier stages of development

Section 2.2 Summarises investments or decarbonisation plans currently announced, exploring the reasons for and implications of investments

Section 2.3: Outlines the limited progress in Carbon Capture (and utilisation/storage) from integrated steelmaking sites, expanding on why this is not considered as a preferred option for decarbonisation of primary iron and steelmaking for the UK

Section 2.4: CapEx and OpEx estimates for low net emission DRI iron production; Infrastructure requirements – e.g. electrical supply, hydrogen generation or supply, iron ore processing, transport links, site footprint

2.1 Steelmaking Technologies and Decarbonisation

Background

Production of steel at just under 2 billion tonnes per annum is second only to that of cement in terms of global scale for bulk materials. Both are high temperature energy intensive processes which have traditionally been based upon use of fossil derived carbon-based feedstocks.

Carbon dioxide from steel production accounts for between 7% and 9% of man-made global emissions. Decarbonisation of the process route is imperative in order to reach UK and global targets for CO_2 reduction.

Two processes currently dominate world steel production. These are:

- The integrated steelmaking route, which is based on reduction of iron ore using coke in a blast furnace (BF), followed by refining using supersonic oxygen blowing in a basic oxygen furnace (BOF).
- The electric arc furnace route, which is based upon remelting of recovered scrap metal using electrical energy.

Approximately two thirds of world's steel is currently made by the integrated BF/BOS route and one third by the EAF route. In both cases there are subsequent process stages to refine the crude steel to achieve the precise chemistry and properties required for its end use. These subsequent stages are common to each route.

The integrated route (BF/BOF) is a majority primary iron process, using the primary iron from iron ore reduced to liquid iron in the Blast Furnace, but may also incorporate significant amounts of scrap for economic purposes.

The EAF route is a majority scrap-based process which may incorporate primary iron for quality purposes, in which case it may come from solidified blast furnace 'pig' iron or from Directly Reduced Iron (DRI) whereby iron ore is reduced to porous solid 'sponge' iron by reacting it with coal gas, natural gas or hydrogen.

2.1.1 Technical capability - Blast Furnace/Basic Oxygen Furnace

The blast furnace is a packed bed reactor in which the raw materials of iron ore, coke and lime based fluxes are added at the top and gradually descend whilst reacting to produce iron. The porous structure within the furnace is provided by the coke and this also reacts with injected oxygen to produce carbon monoxide gas which is able to reduce the iron oxide, forming liquid iron.

$$Fe_3O_4 + 4CO = 3Fe + 4CO_2$$

Carbon-saturated iron

The presence of coke results in the liquid iron becoming saturated with as much carbon as it is able to dissolve, around 4%.

In the next stage of the process oxygen is blown at supersonic velocity into the carbon saturated iron in the basic oxygen furnace. This oxidises away the carbon, whilst providing heat for the process. The result is a basic low carbon steel product. The heat generated also helps smelt a small proportion of scrap (15%-25%) which is added to the BOF to help increase process yield. Downstream refining stages are used to trim the chemical composition and add alloys required achieve the final intended composition.

The BF/BOS route is highly efficient in producing ‘clean’ steel from predominantly virgin raw materials as these tend to be free of contamination from other elements. This results in metal from the BF/BOS which is very pure in terms of having few contaminants. By contrast scrap based melting typically brings a higher level of these undesirable ‘residual’ elements.

Positive pressure preventing air ingress

Also, both the BF and BOF process stages produce a gas which means that the reaction vessels operate at a small positive pressure which prevents ingress of air. This reduces opportunities for nitrogen from the air to be absorbed into the steel. Typically steel from the BOS has less than 20 parts per million of nitrogen.

Chemically clean steel

This chemical cleanness means that BF/BOS steel is a suitable starting point for many steel grades. Steels with low levels of ’residual’ element contamination and of nitrogen are well suited to a range of specialist applications where high levels of formability are required (e.g. automotive sheet) and these factors are also critical in prevention of defects and deterioration in stringent environments.

Throughout the past 50 years the BF/BOS route has dominated world production for several reasons:

- Economy of scale
- Cleanliness of the steel
- Versatility of steels which can be produced, and speed of operation (vs EAF and older technologies such as Open Hearth smelting)
- Historic low cost of carbon. (Cheaper than electrical energy over most of this time)
- Opportunities for recycling uncombusted gases within the plant
- Scrap supply and quality limitations

2.1.2 Technical capability – Traditional Electric Arc furnace (EAF)

The electric arc furnace process remelts scrap steel (or other metal) using a high temperature electric arc

Any grade CAN be made in EAF
Historically there was a view that EAF production was limited to production of standard grades not requiring the most stringent quality standards. This is a misconception. Technically any steel grade can be made via the EAF route given the correct mix of raw materials, process control and subsequent refining steps. For example, the most stringent grades for aerospace and nuclear application have traditionally been made via the EAF route.

However, in some cases where extra control measures are required these can impact on process time and economics. The dominance of the blast furnace/BOF route through the 20th century was based upon its ability to produce large volumes of high quality steel economically. A key factor in this was that carbon-based energy was cheaper than electrical equivalent. The requirement for industrial decarbonisation now changes the assumptions which favoured the BF/BOS route.

Scrap, nitrogen and electricity
There are two key technical challenges for production of high quality steel by the EAF route, quality of scrap and control of nitrogen. The third challenge is economic in ensuring fair competition between electrically produced steels and competitors who have not decarbonised. The basic statement in the following paragraphs will be elaborated in subsequent sections.

In EAF steelmaking, liquid steel produced is influenced by the type and quality of scrap and feedstock used. This brings a higher susceptibility to the presence of ‘residual’ elements from the scrap charge used, some of which such as copper and tin can be detrimental in high specification products.

Air ingress
Unlike the BF/BOS process the EAF route does not typically operate at positive pressure and the process fume extraction can draw in air in the vicinity of the metal bath. This provides an opportunity for the pick-up of nitrogen from the atmosphere. For this reason electric arc furnace steels tend to have higher nitrogen content than those from the BF/BOS route.

The third challenge is economic in ensuring fair competition between electrically produced steels and competitors who have not decarbonised.

2.1.3 Technical limitations of a simple transition to electric arc melting.

A simple transition would involve ceasing to use BF/BOS production and replace this by Electric Arc Furnace technology melting scrap.

This has a number of limitations:

i) Whilst many steel grades can be made from a 100% scrap charge there are a significant number of products for which use of scrap alone will fail to achieve the required levels of steel purity. This is due to the presence of ‘residual’ elements as contaminants in the scrap which cannot practically be removed from the steel.

Steel qualities which can be made relatively straightforwardly from a 100% scrap based mix include:

- Most construction grades
- the more standard parts of the plate, flat and strip product portfolios.

These steels make up around 80% of the bulk carbon steels market.

The steel qualities which present significant challenges and cannot be economically be made from 100% scrap based melting include:

- The highest quality strip products (e.g. some exposed automotive sheet, high-end packaging applications including beverage cans)
- the highest quality plate for line pipe
- high quality long products such as high quality rail, high strength wire,
- some electrical products
- some niche applications (e.g. melting base iron and cathode bar)

For these products, even after allowing for improvements in scrap sorting and quality control, the presence of residual elements in the scrap must be mitigated by replacement of some or all of the raw materials mix by clean iron units derived from iron ore.

The UK’s bulk steel producers who are currently planning to transition from BF/BOF to EAF steelmaking estimate a need for between 15% and 25 % of virgin iron in their **total** product mix. The exact proportion will vary with steel grade. This ranges from zero for most grades to as much as 50% for some of the most stringent qualities.

ii) Many steels require control of the level of nitrogen in the product. Nitrogen can produce effects resulting in embrittlement and crack sensitivity.

The main source of nitrogen in steel comes from contamination from the air.

In the blast furnace/BOS process route this is largely mitigated by the fact that both processes create gas which results in positive pressure within the reaction vessels. This prevents air ingress, whilst the ore based feedstock brings a lower level of nitrogen within the charge material than a scrap based charge. The result is that nitrogen levels around 20 parts per million are typical.

In contrast a scrap melting EAF operates at ambient pressure which is slightly reduced by suction from the fume extraction. This draws in secondary air resulting in greater opportunity for nitrogen absorption either directly or via the arc. An unshielded electric arc can break down air creating an ionised plasma from which the absorption of nitrogen into the steel can occur more easily. In addition the scrap itself brings a level of embodied nitrogen from its previous application.

The result is that for a ‘scrap only’ EAF typical nitrogen levels lie between 50 and 100 parts per million. This is satisfactory for around 80% of current steel grades, but for the remainder additional effort is needed to achieve lower nitrogen levels.

Process carbon for nitrogen control and electrode efficiency

Nitrogen control in the EAF is based on a combination of preventing it from entering the steel and flushing it out. Both of these depend on use of some process carbon.
The associated CO_2 footprint depends on its origin. Carbon reacts with oxygen in the liquid metal bath creating carbon monoxide bubbles, as these rise through the melt they gather and remove some of the dissolved nitrogen.

A second important effect of the carbon-oxygen reaction is that these gas bubbles cause the slag to foam. The layer of foaming slag helps to insulate the surface reducing likelihood of nitrogen pick up from the atmosphere and also covers the tips of the electrodes. An unshielded electrode can radiate more than half its energy to the surroundings rather than into the steel whilst also causing ionisation of the air leading to nitrogen absorption. Foaming slag helps to improve both energy efficiency and in nitrogen control.

The benefits of slag foaming are summarised in Figs 4 & 5:

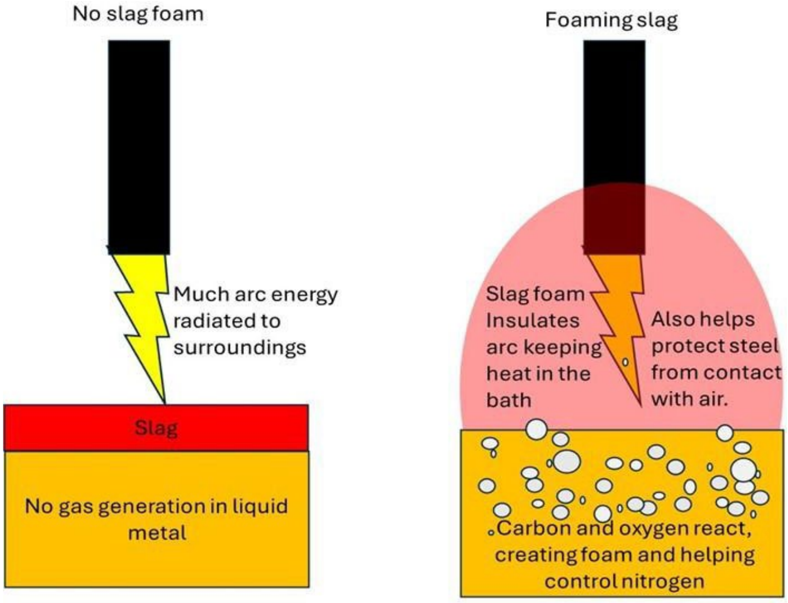


Figure 4: Benefits and mechanism of slag foaming

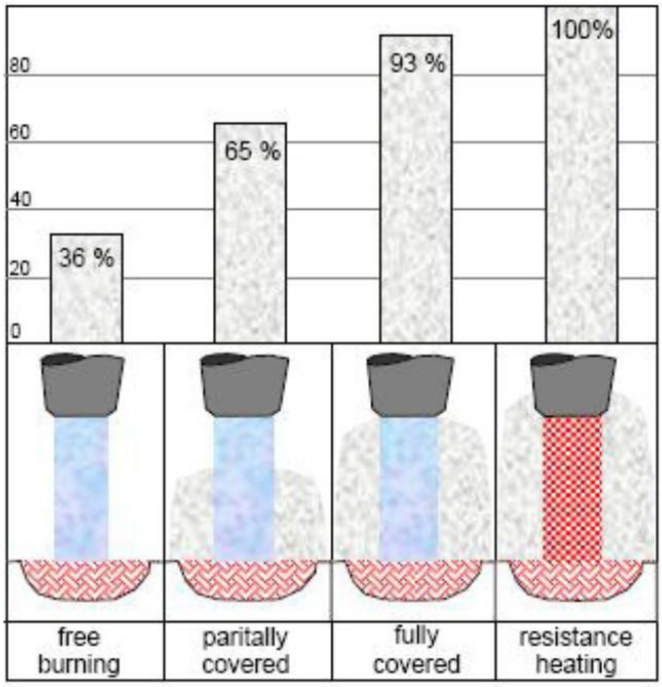


Figure 5: Foaming Slag Effect on Arc Efficiency

In this way the nitrogen content can be brought down to nitrogen levels around 20 parts per million similar to those from the BF/BOS process route.

The carbon required can be supplied either incorporated in virgin (ore-based) iron units (pig iron, DRI, HBI) or by carbon injection. Carbon dissolved in the ore-based input iron is considered to improve furnace efficiency and turnaround ('tap-to-tap') times by lowering the initial melting point of the iron and by reacting more rapidly and consistently within the molten steel. However, carbon injection is common practice where charge carbon is inherently lower, i.e. 100% scrap charges, but also when melting DRI reduced with 100% hydrogen since this is inherently free of any carbon and has a higher melting point as a result. For this reason, DRI providers currently recommend the most efficient path for EAF operators, to be adding process carbon as dissolved carbon in nominally hydrogen DRI, by retaining 20% natural gas (or biomethane) to 80% hydrogen in the DRI furnace.

As noted, a scrap-only furnace charge would be capable of meeting the nitrogen requirements for around 80% of steel products. Those requiring additional control including addition of virgin iron units are typically those requiring high levels of formability where brittleness might be an issue.

This is a similar list to those requiring virgin irons units for steel cleanness purposes:

- The highest quality strip products (e.g. some exposed automotive sheet, and packaging applications including beverage cans)
- the high quality plate for line pipe, and
- high quality long products such as high strength wire, some electrical products and ultra-low alloys materials such as melting base iron and cathode bar)

iii) Economic challenges relate to understanding the optimum balance between materials, energy and processing costs.

It should be noted that processing cost also includes time. Technically any steel grade can be made via the EAF route but not all grades can be made economically if the number of processing steps and time involved becomes excessive.

The most critical factor is energy costs. It is a misconception that electric melting always equates to zero carbon steelmaking. Successful EAF steel producers around the world supplement electrical energy with supplementary forms of energy including natural gas, fossil coal, biogenic carbons and waste materials. There are two main reasons:

- In most regions, carbon-based energy has historically been cheaper than electrical energy. Even today, and including carbon cost measures, this is still the case in the UK. To encourage decarbonisation by reducing dependence on secondary energy input would require further incentives to make electricity pricing more competitive with respect to carbon.

- The second advantage of secondary energy input is to increase the rate of melting and productivity compared to heating with electric arcs alone. Secondary burners can also be positioned to eliminate cold spots which might be process bottlenecks.

Other economic factors concern aspects such a control of nitrogen and other elements such as chromium, phosphorus and sulphur. A balance must be struck between additional time which may be needed to meet some of the higher technical specifications and productivity. Unless the product premium is high enough it may be better to make more of a simpler grade than to ‘waste’ resource on some of the higher qualities. Ultimately, that market will still require all of these materials, but the pricing balance may take time to adjust resulting in a competitiveness time lag between producers who have transitioned to EAF production and are incurring slightly increased costs and non-transitioned producers offering a lower price. Carbon pricing mechanisms will need to be sufficiently timely and nimble to ensure fair competition.

2.1.4 General technology pathways to decarbonisation

In moving away from the historic dependence on the blast furnace/BOF route there are several options with differing merits and challenges: (3)

- Blast furnace
    - With option such as carbon capture and utilisation and carbon substitution

- Electric arc furnace process
    - With various additional options to increase effectiveness
    - and variants such as submerged arc and smelting reduction (ESR furnace)
    - and differing levels of use of virgin iron units
- Induction melting
- Electrolytic or chemical reduction

In this section we will briefly note the technical principles, with regard to reducing the CO_2 impact on steelmaking performance and the role of virgin iron units

2.1.4.1 Decarbonisation challenges for Blast Furnace and Basic Oxygen Steelmaking

This route is commonly known as integrated steelmaking and begins with reduction of iron ore.
Its technical capability was noted in **Section 2.1.1**

Advantages:

1. The process is highly efficient, produces a very clean liquid steel feedstock with good control or carbon, oxygen, sulphur, phosphorus and nitrogen.
2. If there were no concerns over carbon footprint and if production facilities can be fully loaded this is the most cost-effective means for producing liquid steel in bulk.

Disadvantages

1. The disadvantage is that this is a carbon-based process resulting in an end product with embodied carbon of around 1.9 t of carbon dioxide per tonne of liquid steel – with best practice short of carbon capture this can be reduced to around 1.6 t/tonne whilst a theoretically perfect system might achieve ~1.4 t/tonne.
2. Another disadvantage is that the integrated route is hugely capital intensive requiring not only the blast furnace and basic oxygen furnace but coke ovens and sinter plant to supply raw materials and intermediate processes such as primary desulphurisation.
   Such a plant is much more expensive to set up, staff and maintain than an electric arc plant of equivalent output.
   For effective operation such plants require economies of scale and large/reliable order books. Break-even typically requires >80% asset utilisation.
3. Process must operate continuously. This process does not respond well to up-turns, down turns or stoppages in production nor to rapid variations in feedstock.
4. Asset life. The high capex requirement for this process route requires that the asset must produce over a longtime frame in order to pay back on investment. A blast furnace lining is expected to operate for >20 years. Investment decisions must therefore be taken with a high degree of certainty on future market trends.

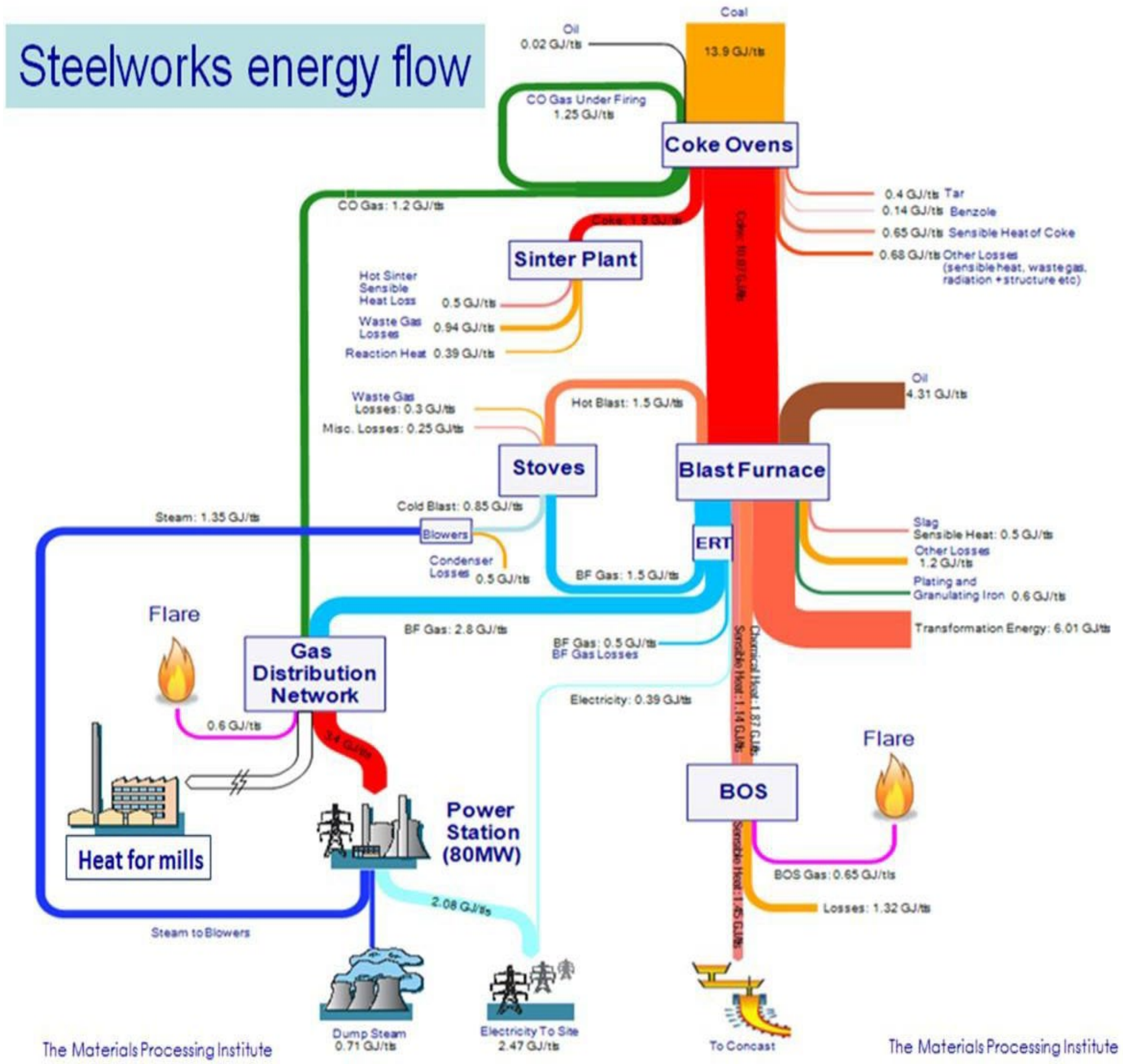


Figure 6: Integrated steelworks energy flows

2.1.4.2 Blast Furnace: Options for carbon mitigation

Carbon capture and storage. (CCS)

A summary of a comprehensive review of CCUS options for BF/BOF steelworks is found in Appendix 2.

In principle, the carbon produced by the BF/BOF route can be captured and stored, or re-used. Technically, this is a possible solution. In practice there are a number of challenges:

1. Carbon dioxide emissions do not all occur in one place, Coke, sinter making, blast furnace, oxygen steelmaking and intermediate movements of materials all create CO_2. Any capture system needs to have multiple sub-systems which add to capital and operating cost.
   Moreover, the process gas is not CO_2 but a mixture including unburned carbon monoxide, nitrogen and hydrogen (from coke making).

2. Who would build it and when? Having discussed the future market for new blast furnace development globally with two major steel plant manufacturers, the views expressed suggest more than 100 schemes either under way or under discussion, but none involve carbon capture. This would suggest that in terms of timing commercial uptake is still many years away. The only known examples are pilot scale demonstration units (one Europe and one in Asia)

3. There must be local infrastructure to accommodate the collected gas. This is highly dependent on geography. (e.g. For the UK this would be much more challenging in Wales than the on the east coast due to availability of collection and pressurisation infrastructure and suitable geology.)

4. Retrofit: Existing UK plant is old, leaky and was not designed with carbon capture in mind. This presents a massive challenge if retrofit is considered. The challenge would be simpler for a ‘new-build’ solution, but even here the appetite is limited.
   In order to achieve maximum energy efficiency it would be best to harvest this energy whilst burning the gas through to CO_2. One option for this is to channel all process off-gases to a power plant and then collect the resultant gas

5. A further complication is that most of the gas streams from integrated steelworks are ‘dirty’ by comparison with many processes used for development of carbon capture systems. In particular oxides of sulphur and nitrogen and particulates are a concern. These add further technical challenge and uncertainty on long term operating costs.

6. Cost. Steel is a globally traded commodity with slender profit margins. In terms of both Capex and Opex, carbon capture adds significantly to expense. Unless significant changes were to occur in terms of protections linked to carbon footprint investment is highly unlikely.

Carbon capture and utilisation (CCU)

Another option being piloted at University scale in the UK and Europe and also at pilot scale in Sweden and Belgium is to use the CO or CO_2 gas as raw materials for the synthesis of hydrocarbons such as methanol. A mobile demonstrator unit has been trialled on UK steel plants by the University of Sheffield

Again, this option is technically feasible, but the technology requires several additional years of development for scale-up to industrial capability, followed by the necessary steps for plant building and installation. At this level of readiness this is unlikely to form a part of the short-term strategy for the UK.

The technical considerations noted for CCU still apply

Scrap additions

There is scope for scrap addition to the blast furnace but the extent is limited to around 25% by the need to maintain a stable furnace structure and the requirement that the scrap be of sufficiently low melting point and in size ranges compatible with the furnace burden.

Other opportunities to reduce blast furnace CO_2 footprint

Other opportunities for carbon dioxide reduction exist which are based upon reducing the level of coke use since this is the primary source of CO_2. Coke provides both the porous structure in the blast furnace as well as reductant. These aspects can theoretically be separated allowing the use of coke to be primarily for furnace structure whilst the heating and reduction could be provided by additions of other materials.

1. Carbon injection: This is well known technology and is already well practised and maximum feasible additions rates are known. Therefore it is unlikely that significant further reductions will be found. However, the traditional approach of coal injection might be replaced by more sustainable forms of carbon (e.g. bio-carbon).
2. Gas injection: The principle is similar to carbon injection but since methane is a hydrocarbon the carbon footprint is reduced. Again, this technology has already been used so the additional benefit likely to be derived is low.
3. Hydrogen injection: In principle this is a feasible option for reducing the overall CO2 emission of a blast furnace and achieving ore reduction and heating - Nippon Steel claimed a 43% reduction in blast furnace emissions in a 2024 press release (4) - but is still at best, at industrial demonstration phase due to limited hydrogen availability for sustained campaigns, and several technical challenges and uncertainties:
    a. Availability of bulk hydrogen is still far off
    b. Hydrogen price is uncompetitive
    c. Control of high flow rates of injected hydrogen
    d. Effect of hydrogen concentration on blast furnace refractories, which are largely silica-based is unknown. Potentially these may be reduced.

However whilst offering some reduction in carbon use these techniques could not eliminate the participation of coke in the blast furnace reactions and without some continuous replacement of coke the structural effectiveness of the furnace structure is likely to deteriorate.

2.1.5 Carbon Efficiency and Carbon Footprint within the EAF process

Electric Arc Furnace steelmaking is much lower emission but not carbon free
Electric arc furnace melting based on scrap allows significant reduction in carbon dioxide emission compared to the 1.9 tonnes CO_2/tonne of liquid steel associated with the integrated (BF/BOF) steelmaking route, but the process is not carbon free and the degree of improvement will vary significantly. Depending on the electricity grid carbon intensity, the furnace design and operating practice chosen the carbon footprint could be as low as 0.2t CO_2/tonne of liquid steel, or as almost as high as for the integrated route.

The key factors are:

2.1.5.1 Energy Efficiency

Energy and materials are the two most critical costs in EAF steel production and modern EAFs aim to optimise energy efficiency wherever possible:

1. **Hot charging of materials improves overall efficiency and productivity:** Process waste heat should be utilised. Depending on furnace design this can be used to preheat scrap either via shaft or tunnel furnaces, thereby reducing the energy requirement when the scrap enters the furnace.

   This also has the advantage of reducing melting time resulting in additional energy saving from (electrical) losses during ‘power on’.

   Fig. 7 shows this concept schematically for the Consteel, one of several commercially available EAF plant options including continuous scrap heating and feeding:

   Some of the new developments proposed for the transition from integrated to electric steelmaking also apply the same concept to the addition of virgin iron units where required.

   Co-location of direct reduction plant on the steelworks site can allow the facility for hot feed to the furnace without allowing the material to become cold.

   There are a few examples worldwide of co-location of blast furnaces, or mini smelting units alongside EAF plans allowing charging of liquid iron to supplement the scrap charge.

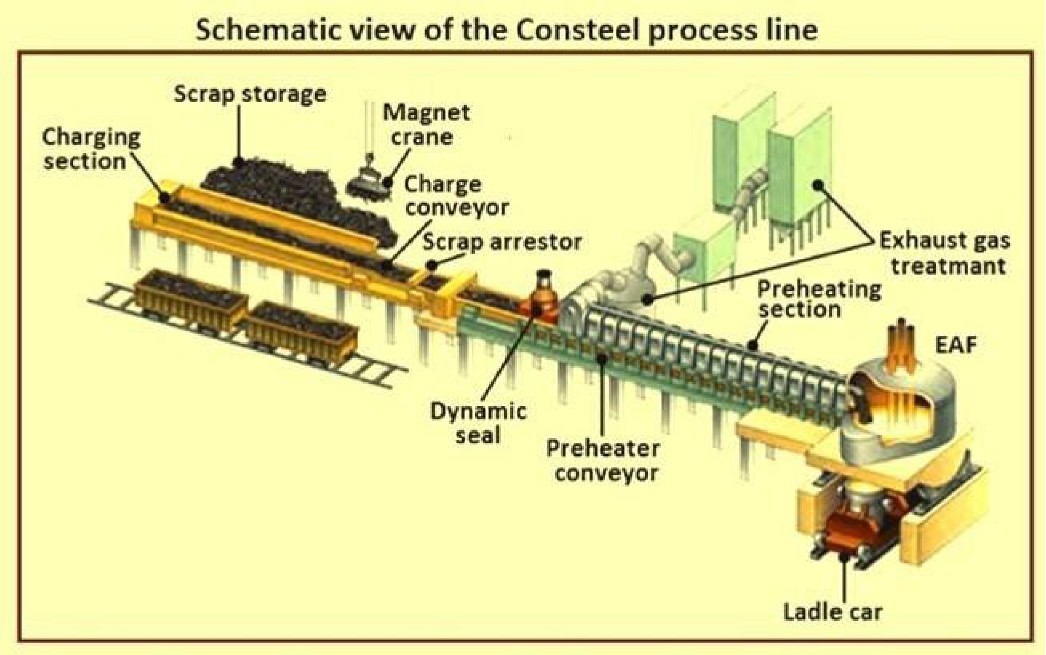


Figure 7: Consteel concept with preheating

2. **Slag foaming increases efficiency and electrode lifetime but emits CO_2:** This was noted in Section 5.3. An exposed electric arc radiates much of its heat to the surroundings rather than usefully into the metal. Up to 50% of energy can be lost and there is added wear and tear on exposed furnace components. The principle of slag foaming is to create a low density slag which submerges and protects the electrode tips.

   This ensures that the energy from the arc is confined within the steel/slag system giving more effective heating and avoiding wasteful radiation to the surroundings. In addition the slag foam both insulates and protects the surface of the molten steel bath.

   The downside of slag foaming is that the gas required to create slag foam arises from the reaction of carbon and oxygen and thus some CO_2 is created. However, the overall effect of slag foaming is beneficial in terms of energy efficiency. Steelmakers have been looking to mitigate the net CO_2 emissions aspect by trialling use of bio-carbons rather than fossil fuels to promote slag foaming.

3. **Secondary energy input may account for 50% of the energy balance**: Overall commercial efficiency depends on using the most efficient and cost effective use of process energy. This was noted in Section 5.3. Use of electric heating alone increases melting time in the furnace leading to a higher proportion of energy being lost and also to reduced productivity.

   Historically, carbon based energy was (and is) cheaper in the UK and many parts of the world than electrical energy, leading to EAF design relying on significant additional energy input via sidewall burners and carbon injection systems. Systems used include gas, oil and powdered coal (or biochar) based burners or jet injection systems. Up to 50 % of process energy may be added in this way.

   Except in areas of very cheap electricity this is likely to remain the common practice. However, as noted under ‘foaming slags’ use of bio-fuel alternatives to fossil based energy are now being explored.

2.1.5.2 Effect of electricity supply and carbon footprint

In determining the path towards decarbonisation by electric steelmaking, not all forms of electricity are equal. It is necessary to consider the cost of electrical energy since this determines the necessity and attractiveness of substituting alternative forms of energy. It is also necessary to consider the carbon footprint of the electrical energy.

Currently one UK EAF steelmaker operating from a 100% scrap charge has access to fully green electricity from hydroelectric assets within the group, and estimates their carbon footprint as ~350kg CO_2 per tonne of liquid steel. This probably represents the lowest practical achievable carbon footprint with current UK energy grid. For other producers not able to claim access to fully decarbonised electricity the carbon footprint is likely to be closer to 5-600 kg CO_2/tLS. This ought to reduce as the UK journey to full grid decarbonisation continues.

Some international competitors refer to having access to decarbonised electricity as part of their transitions strategy. Options vary with cheap hydro-electricity available in Scandinavia, a significant nuclear component in the French grid and proposals for enhanced solar capability in southern Europe and MENA countries. A few operators are considering plans to generate their own electricity.

2.1.6 Impact of virgin iron units on carbon footprint

For those grades requiring a proportion of virgin iron units in the mix raw materials mix, the carbon footprint will increase further depending on the process used for the supplied materials. At high dilution levels from fossil carbon-reduced metallics, this may push some EAF-made grades over customer specifications or CBAM thresholds or allowances for low-emission steels.

Section 2.1.6.1 below describes calculations which suggest a ‘green steel acceptable’ limit of approximately 45% dilution for NGDRI and 25% for GPI, based on current EAF practice and UK electricity decarbonisation projections.

Whilst there is no single unifying ISO standard defining “Green Steel” (or low-emission steel) the question is developing and converging rapidly. There are several overlapping systems of voluntary standards, outlined in **Appendix 4** , and all tending to comparable emissions factor trajectories from 2019 to 2050.

Studies into different DRI steelmaking routes give estimates for net embodied emissions ranging from 0.1 t CO_2e/t new steel for H-DRI to 0.3 tCO_2e/t new steel for biosyngas DRI [11,17].

Hydrogen DRI – minimal CO_2 footprint, but unavailable to UK as yet

Hydrogen direct reduced iron will, in theory, add negligible CO_2 footprint but currently faces a high price of green hydrogen, and lack of bulk production infrastructure. In many geographies the aspiration to move towards bulk green hydrogen supply based upon electrolysis at effective costs is and is likely to remain constrained, by electricity price, capex and opex, availability, and the time required to create the necessary infrastructure, whilst blue hydrogen from fossil hydrocarbons + CCS faces acceptability barriers associated with its feedstock.

Promising work in Scandinavia is underpinned by access to cheap surplus hydroelectricity needed for green hydrogen production.

A disadvantage of hydrogen reduced DRI from an operational steelmaking perspective is that it does not contain carbon. This results in a higher melting point than methane derived DRI and also, carbon must then be added to the steel bath in other forms in order to address process needs for slag foaming for energy efficiency and nitrogen control.

In the short term (before early 2030's) this is not likely to be a raw material available in significant tonnages to UK steelmakers from external sources since much of the current asset build is tied to existing steel plants, and several 'full hydrogen' DRI conversion plans have been postponed.

Conventional DRI/HBI – medium CO_2 footprint, supply increasing but somewhat constrained

Direct reduction using methane is a more credible option as a source of virgin iron units with a lower carbon footprint than blast furnace produced materials. Used in combination with green electricity in the EAF this could achieve ~0.75 t CO_2 per tonne of liquid steel. However, currently this material is more expensive than scrap or pig iron.

An additional constraint in the short term may be availability of DRI. The announced plans for steelmakers globally transitioning to the EAF route suggest a projected need for DRI in excess of current supply. This could result in lack of material in the short term, although over time the market can adjust. Many of the main European steelmakers have announced plans for installation of their own DRI capacity which would ensure their own self-sufficiency. Several of these plans are believed to be under review on grounds of capital and operating cost effectiveness. The announced proposals for creation of new DRI production facilities typically claim that these will begin using natural gas reduction but should be 'hydrogen ready' when availability of cheap bulk hydrogen is achieved.

DRI produced from natural gas contains a level of carbon derived from the fuel. This can be between 1% and 2.5% depending on the production route. As noted in discussions on slag foaming, energy efficiency and nitrogen removal, this can be beneficial in terms of steelmaking efficiency. A level of 1% to 1.5% is considered optimum.

UK producers have announced no plans to invest in sovereign capability for DRI, although UK steelmakers say they would be keen to buy green DRI 'at the right price'.

Pig Iron – widely available but high CO_2 footprint

The third choice where alternative iron units are required to achieve product quality is the addition of pig iron (preferably granulated pig iron, GPI). This is anticipated to be the preferred choice in the short term for both major UK steelmakers making the transitions to EAF, although they will both be aiming to meet steel specifications using as near as possible to 100% recycled steel feedstock . Advantages are that both producers are part of larger international groups which allows them access to this material. In anticipation of an upturn in demand for GPI some existing blast furnace operators are exploring the addition of the relatively simple pig iron granulation equipment. The disadvantage is that pig iron comes with the full carbon footprint of a blast furnace produced material to which must be added any further factors associated with the EAF processing route. At low levels of virgin iron dilution of scrap this may not be a major problem for customers of the steel, but at higher levels of use the resultant carbon footprint may be comparable with integrated route steels. A judgement would be required on whether, and for how long, this will meet customer expectations on decarbonised product, given competitor products using the DRI alternative. An eventual planned transition to lower carbon feedstock will be essential to meet net zero targets and markets.

As noted above the steelmaking process benefits from some form of carbon in the liquid metal bath to promote slag foaming. Pig iron is carbon saturated (>4% carbon) and meets that requirement. However where large proportions of pig iron may be required for scrap dilution this high level of carbon may then be excessive compared to the process need, at which point it begins to substitute for some of the secondary energy which might otherwise be employed. The process energy gain as well as the lower melting point of pig iron compared to DRI/HBI can assist in faster turn-around (tap-to-tap) times in EAF operation, another reason for its ongoing popularity with plant operators.

A technical challenge in the use of pig iron can be the sulphur content which is routinely removed by a separate process prior to oxygen steelmaking in the BF/BOS process route but may require additional processing via the EAF route.

2.1.6.1 Scope 3 and carbon footprints – the impact of OBM choices on emissions factors

A broad brush summary model was created to demonstrate the interplay of different working assumptions about steelmaking options, on carbon footprints, ie the CO_2e/TLS and the relative magnitude of Scope 1,2, and 3 emissions.

The variable factors were scrap-to-OBM ratios, OBM type, EAF practice including the use of gas and coal for heating or process reasons, and the emission of CO_2 as Scope 1 (carbon which was present in and lost from the OBM or carbon furnace additions), Scope 2 (power grid carbon intensity), and Scope 3 (upstream carbon emissions from the production of the OBMs).

Figures 8 & 9 below are visual outputs from the model, which suggests that for dilution factors above around 45%, only the use of H2DRI (or similarly low emission iron) will be able to keep the carbon footprint of the final crude steel below the expected 'green steel' market threshold of 600 kg CO_2/tonne of steel. **Use of pig iron in such a 'green steel' would be acceptable below around 25% dilution using these assumptions.**

Both Figures 8 and 9 are showing a range of 'Green Steel' standards' miniumum expectations in pink highlighter, see **APPENDIX 4** for explanation of the most prominent approaches and their threshold values.

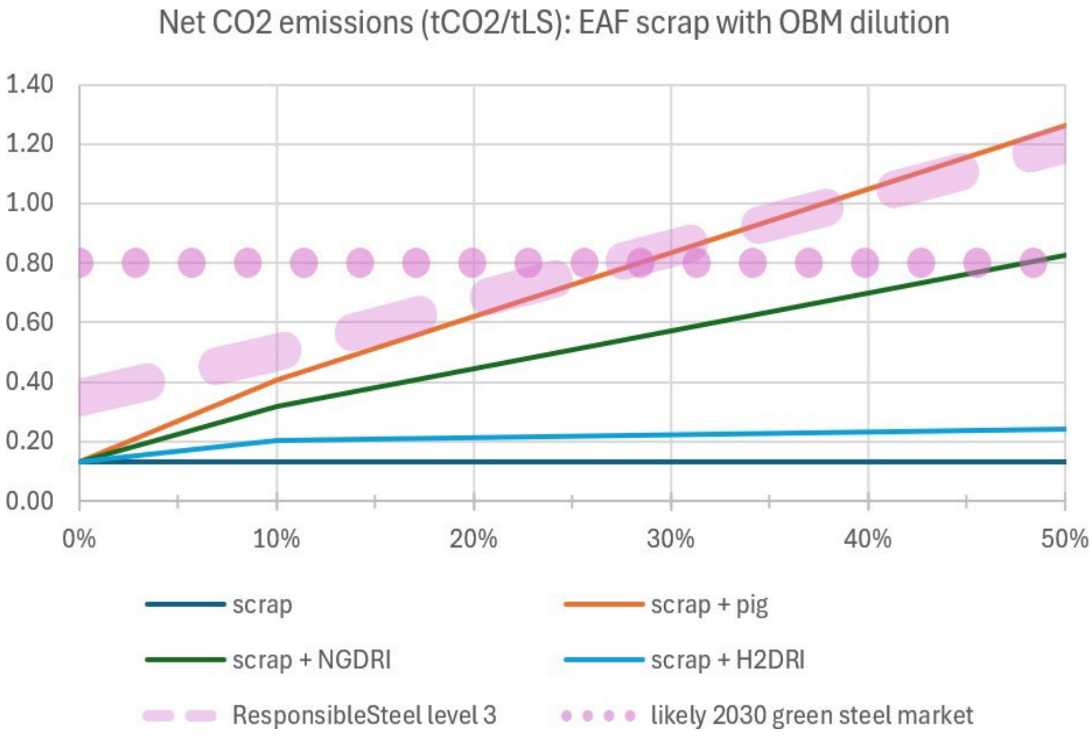


Figure 8: Net CO_2 emissions per tonne vs % dilution factor of scrap with pig iron or different DRI

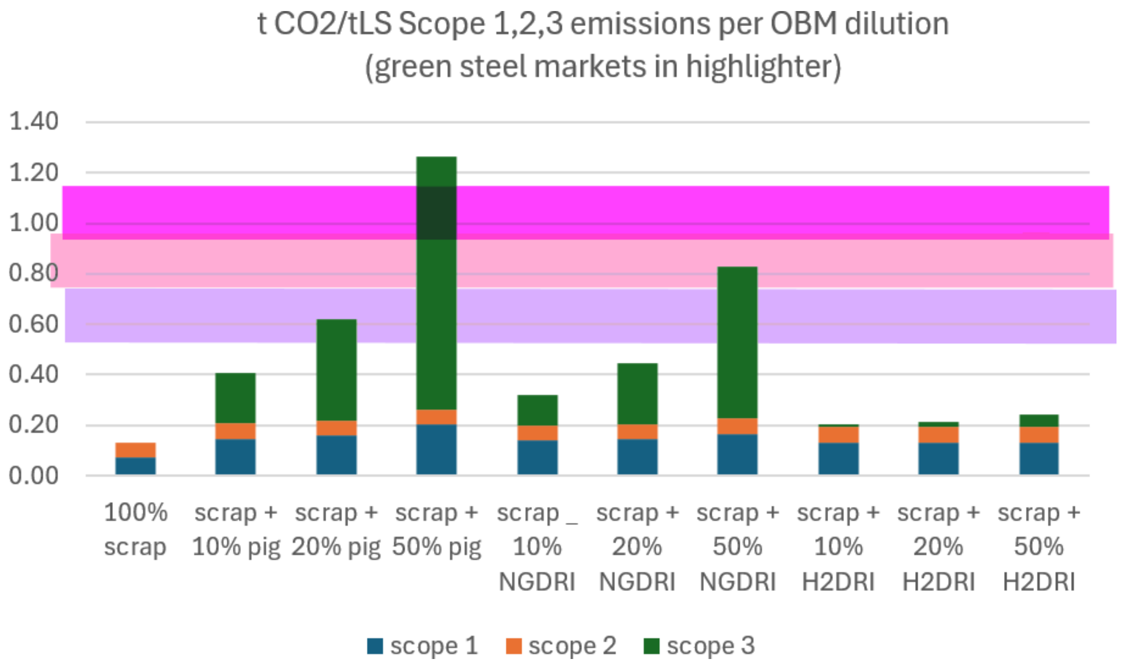


Figure 9: Total CO_2 emissions, broken by Scope 1,2,3 for a generic EAF steel made with scrap plus varying levels of pig iron, Natural Gas DRI (NGDRI) or Hydrogen DRI (H2DRI). Overlaid in pink with the range of likely market definitions for acceptable 'green steel'. The most significant factor to future acceptability in this model, are the scope 3 emissions ie those emitted when producing the pig iron or DRI in the first place

Adding these assumptions to Table 2 in Section 1 shows a range of scenarios for UK domestic steel sector emissions under the ‘back to business as usual’ 40% supply scenario, capturing the scope 3 emissions (see table above) from the original production of the various ore-based metallics, **production of which may or may not be offshored**

domestic supply of 'mill products' to UK market	annual tonnage of steel	x	% of OBM required for steel quality	=	tonnage of OBM	tonnage of scrap	CO2 footprint EAF + scrap only	CO2 footprint scrap + GPI	CO2 footprint scrap + NG-DRI	CO2 footprint scrap + H2-DRI	CO2 footprint prior to 2027
rebar	700,000	x	0%	=	0	700,000	92,000				92,000
plate	750,000	x	10%	=	75,000	675,000		259,000	198,000	111,000	1,350,000
construction long products	1,000,000	x	15%	=	150,000	850,000		452,000	331,000	155,000	1,800,000
special forgings, aerospace	800,000	x	10%	=	80,000	720,000	95,000	276,000	212,000	118,000	95,000
specials - ppe, construction	800,000	x	25%	=	200,000	600,000		533,000	371,000	137,000	1,440,000
Hot rolled coil, standard	2,500,000	x	20%	=	500,000	2,000,000		1,398,000	994,000	409,000	4,500,000
demanding hot rolled coil, packaging	300,000	x	50%	=	150,000	150,000		360,000	239,000	63,000	540,000
	7,500,000				**900,000**	6,600,000	**187,000**	**3,002,000**	**2,133,000**	**875,000**	**9,817,000**
Cumulative national steelmaking CO2 footprint (cradle to gate scope 1,2,3):								**3 Mt**	**2.1 Mt**	**0.9 Mt**	**9.8 Mt**

Table 3: Estimated impact of steelmaking OMB:scrap ratios on net UK emissions

2.1.6.2 Carbon footprints of various steelmaking combinations

The combination of technologies used leads to a range of possible carbon footprints for steelmaking processes as shown in Figs 10 and 11.

It should be noted that Fig 11 did not include the option for scrap based EAF production where scrap use is supplemented by pig iron, which is stated as the preferred initial option for supplementary virgin iron units by the two UK steel producers currently transitioning from blast furnace to EAF steelmaking. Pig iron has a larger carbon footprint than the DRI-based options.
An extra bar has been added for the case of 25% and 50% of the charge being supplied in this form. In extreme cases the proportion of virgin iron needed may be higher than this.

In assessing these figures is has also become apparent that there is mismatch in expectations between some of the more proactive supply chain end users and UK steel producers on the extent of the green steel transition. Some UK infrastructure providers have indicated an aspiration to buy steel with a CO_2 footprint of ~350 kg per tonne of liquid steel in the short to medium term dropping towards 100kg per tonne by 2050. Current pathways to transition in the UK will not meet these aspirations, in the short terms and will require a programme towards further decarbonisation measures in the longer term.

Meanwhile, some of the announced plans from European competitors, especially those in Scandinavia with access to fully decarbonised electricity and, in future to bulk hydrogen will go further. **There will be a need to align expectations on steel supplier and consumer sides, preferably reinforced by national industrial policy, or there is a risk of loss of market share to overseas producers.**

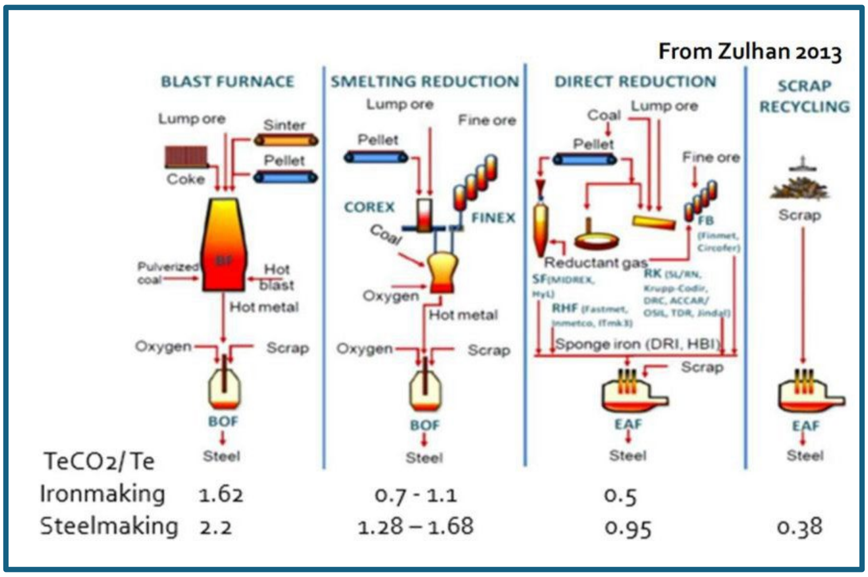
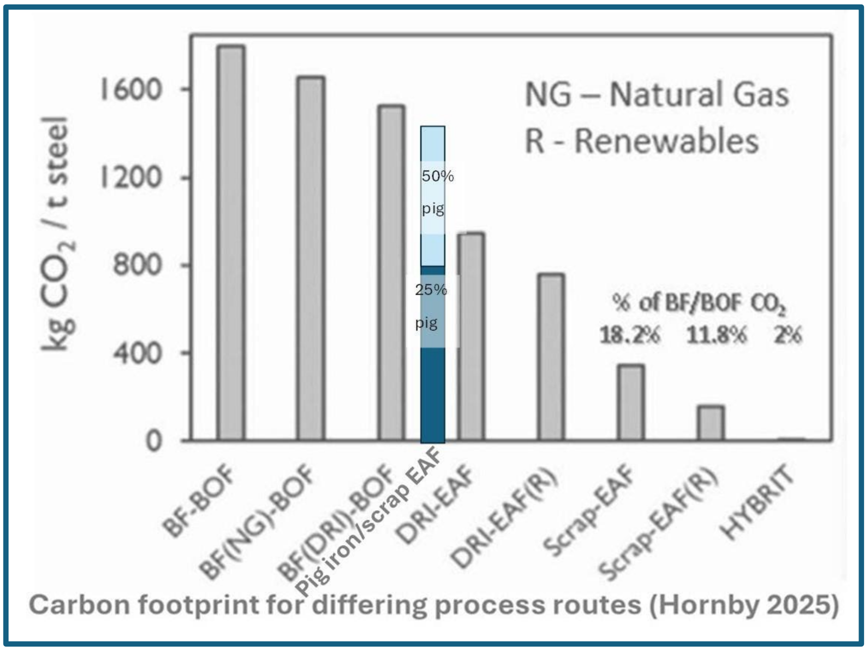


Figure 10: Typical ironmaking and then total steelmaking CO2 emissions factors for various routes



Carbon footprint for differing process routes (Hornby 2025)

Figure 11: Typical emissions factors for various steelmaking route configurations

2.1.7 EAF hybrid variants involving smelting reduction

There are a number of processes which can be considered as hybrid options between the integrated and EAF steel production routes
These involve either in-situ, pre-reduction of iron ore for feeding intro the EAF or reduction in-situ. The objective to reduce the carbon footprint and reduce process energy by making use of these iron units in their hot form rather than having to reheat externally supplied materials from cold. Variants which have bene postulated include:

i) **Blast furnace or mini blast furnace close to the EAF** allowing direct field of liquid or hot solid pig iron. This solution is adopted by one major steel producer in North America which already possessed blast furnaces. In Asia there have been at least two examples of a mini blast furnace sited alongside an EAF plant. Advantages are hot feed of liquid allowing production of steel qualities where high levels of virgin iron may be needed. Another potential advantage is the ability to skim off slag associated with the iron production prior to charging to the EAF unlike use of DRI where non-metallic materials and slag (termed gangue) are carried into the furnace and can result in larger slag volumes.

A disadvantage is that production of blast furnace iron involved the whole embodied carbon content of the process route. Therefore without carbon capture or some form of mitigation, this will noy be the lowest carbon route to steel production. Also the hot metal sulphur content brought into the EAF may be high if there is no opportunity for removal treatments unless an additional process stage is added.

Such an approach only makes practical sense if the scale of iron production can be economically matched to the EAF or there is a market available for any surplus material. However, since different steel grades require varying amounts of virgin iron, the furnace demand is likely to be variable. This is likely to be a more attractive solution for a plant seeking to retain an existing furnace than to install new capacity.

ii) **DRI production unit aligned to allow direct feed to EAF.** Again, this allows hot (solid) feed into the furnace with consequent energy savings and the direct reduced material will have lower carbon footprint than the pig-iron equivalent. The potential energy saving for a hot feed at around 400°C rather than cold is equivalent to around 20% of energy required to heat and melt the material.

The carbon footprint for natural gas reduced DRI is lower that than for pig iron as discussed elsewhere in this report as the primary source of heating and reduction was methane rather than coke, but there is some carbon use. As noted earlier, the DRI will have a carbon content in the range of 1% - 2% which also brings benefits in terms of slag foaming for energy efficiency and nitrogen control.

A disadvantage compared to blast furnace or pig iron addition is the presence of a higher quantity unwanted gangue material present in the ore which could not be removed. This can lead to higher slag volumes affecting both performance and energy use. BHP/Midrex estimated at their 2001 Seminar that for each tonne of DRI added, this might result in additional cost of ~£0.70

In the short to medium term natural gas based DRI is a more likely route than the fully decarbonised use of hydrogen based DRI, which is unlikely to become available at economic cost or production scale in the short term. However, hydrogen reduced DRI has certain drawbacks which are that its melting point is higher which affects melt times and consequently requires a higher hot heel of liquid metal at the start of each melt, which affects productivity. Also, since it contains no carbon there must be compensating additions (ideally sustainable carbon such as bio-char) for slag foaling and nitrogen control.

iii) Direct reduction in the furnace or reaction vessel

Hitherto, discussion of the use of virgin iron units in liquid steelmaking has focussed on addition of materials that have already been reduced in a previous process. It is also possible to carry out the reduction within the reaction vessel.

This can take a number of forms:

a) **Addition of iron ore and reductant to the bath during melting** (e.g. continuous feed of composite ore/reductant pellets or briquettes through the furnace roof). This is theoretically and technically feasible and has been proved at pilot scale for EAF steelmaking but is not available as developed process. The most practical reductant remains carbon (from either fossil or sustainable sources), so the carbon footprint cannot be zero.

b)

Figure 12: Addition of composite ore/reductant pellets to EAF during operation

Advantages are that energy used in the process is all focussed into the steel bath, and slag foaming and nitrogen control can be achieved. Disadvantages are that this is an additional process step within the electric arc furnace which adds to processing time, particularly since the ore reduction reaction is endothermic, requiring extra energy. The rate of addition must be understood and carefully controlled to match available furnace energy input.

The process is well known in the production of several non-ferrous metals by submerged arc EAFs (e.g. Ferromanganese and nickel production) where ore, carbon and fluxes are continuously fed through the furnace roof. React in-situ and slag and metal are drawn off from separate tap holes. This resembles the type of chemical process in the lower parts of a blast furnace but with electrical arc energy providing heating.

These in-situ smelting reduction process may offer some gains in overall energy use but do not significantly decarbonise the production of virgin iron unless they use sustainable carbon sources or were to be combined with carbon capture.

c) **Smelting reduction in a separate vessel**.
In this case reduction of iron ore could be carried out in a separate vessel to provide a feedstock supplementing scrap melting in the EAF.

Examples are the Corex, Finex, HISMELT and HISARNA processes. HISMELT and HISARNA were originally devised to produce iron using forms of ore and carbon that were wastes (fines and dusts). Some reduction of CO_2 is accomplished by comparison with blast furnace ironmaking (about 25%), but these technologies seem less favoured by most steel producers than the DRI options as they remain coal/fossil based.

One advantage is the possibility to carry out some treatment of the liquid iron pool before onward feeding to the EAF or steelmaking furnace. This potentially allows for some slag removal and desulphurisation treatment.

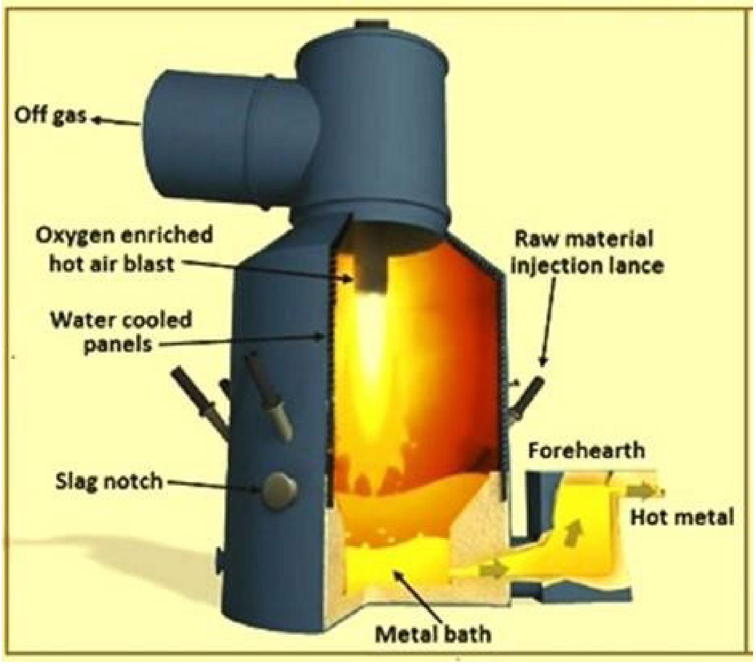


Figure 13: Iron ore smelting

d) **Combined reduction and smelting with hydrogen plasma**
In the longer term future use of hydrogen as a reductant for ore within the steelmaking furnace could be considered, but this is far from being a developed technology.

It is known that there are European and Chinese research programmes which have demonstrated reduction using a hydrogen plasma, standalone or within the electric arc itself. This latter option may require development of hollow electrodes to feed ore to the reaction site. Research is at the early stages and, as yet, unproven at scale. **Adoption would also require availability of bulk cheap hydrogen**.

2.1.8 Alternatives to EAF

There are two other developed technologies for steel melting and ore reduction, which are included below for completeness. However, these are both more suited to specialised niche applications than the needs of bulk steelmaking:

2.1.8.1 Induction melting

Another technology applicable for scrap based steel is use of induction melting. Induction furnaces melt metals by means of alternating electric fields which induce electrical currents within the scrap or metal charge. Combined with resistance of the metal this creates heat resulting in melting of the metal.

In terms of steelmaking capability, it is theoretically possible to accomplish most of the product range achievable by EAF except that the scope for 'active' steelmaking such as oxygen blowing and carbon injection is less practical for induction melting, limiting the scope to steelmaking operations which can be accomplished by melting and alloying.

A further variant is vacuum induction melting which can be used where atmosphere control is required to limit reoxidation and to assist nitrogen removal.

Induction melting is normally limited to small scale work (some foundry applications) and specialist engineering applications. It is not likely to supplant bulk steelmaking processes because of physical size vs power considerations: the required electromagnetic field penetration becomes less effective due to the screening effect of the metal when applied to larger volumes.

The UK has one significant producer (Union Electric Steel) using induction melting to make castings of up to 80 tonnes for highly alloyed specialist spin cast applications such as hot rolling mill rolls.

This melting option covers a very small proportion of the UK's steel production and can be adequately serviced by use of selected specialist scrap and alloys. No significant requirement of procurement and use of virgin iron units is envisaged.

2.1.8.2 Green iron production by Electrolysis

Another technology applicable for production of green iron is by electrolysis.

Electrolytic ironmaking is a known technology and electrolytic iron is a standard traded product. Electrolysis can be applied either to a hot process using molten oxides or cold using dissolved raw materials.
The product is essentially pure iron without other contaminants. For many applications, except for the most stringent needs, this is an impractically pure form of iron since some useful 'missing' elements found in other production routes have to be added to achieve steelmaking requirements.

The carbon footprint is simply that associated with the source of electricity used, which would be zero with a fully decarbonised supply.

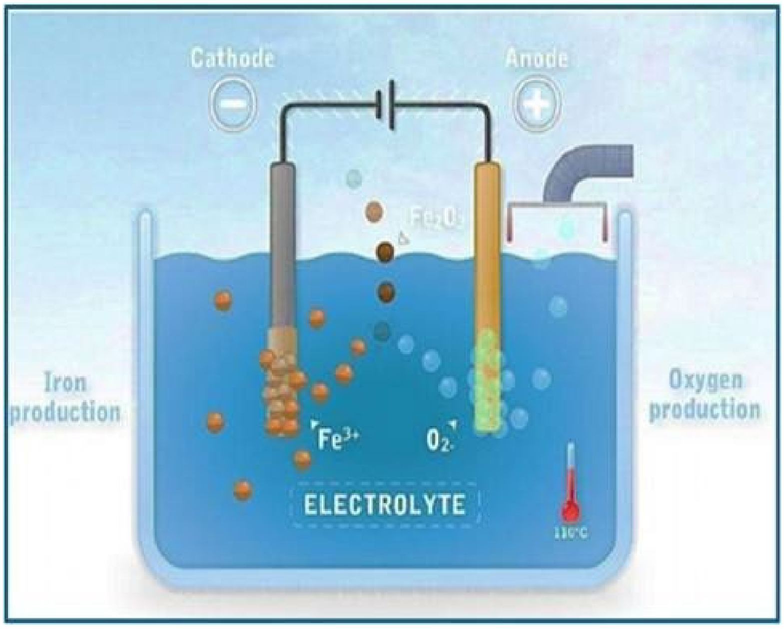


Figure 12: Iron winning by electrolysis
(NB the electrolyte is blue in this picture but it could be aqueous or non-aqueous)

However, the production rates associated with electrolysis are not easily upscaled to the massive volumes associated with bulk steel production. The physical footprint and logistics of iron collection from the thousands of modular reduction cells required to service a Mt-scale iron demand is also a significant factor facing the technology. As a result this is currently a niche source of iron units for specialist applications (sold as virtually pure Fe “Electrolytic Iron”) and is not a near term economic prospect as a source of clean virgin iron units for bulk steelmakers. The internationally traded cost is currently more than ten times higher than for other forms of virgin iron such as DRI.

Although there is development work internationally to improve electrolytic iron production using various electrolytes and chemical pathways, and a commercial demonstration unit in South America, there is no short term prospect yet emerging at scale which appears likely to bring either productivity or cost in line with that required by bulk steelmakers in the 2020s.

2.2 Global developments and Investments in low emissions iron reduction and melting

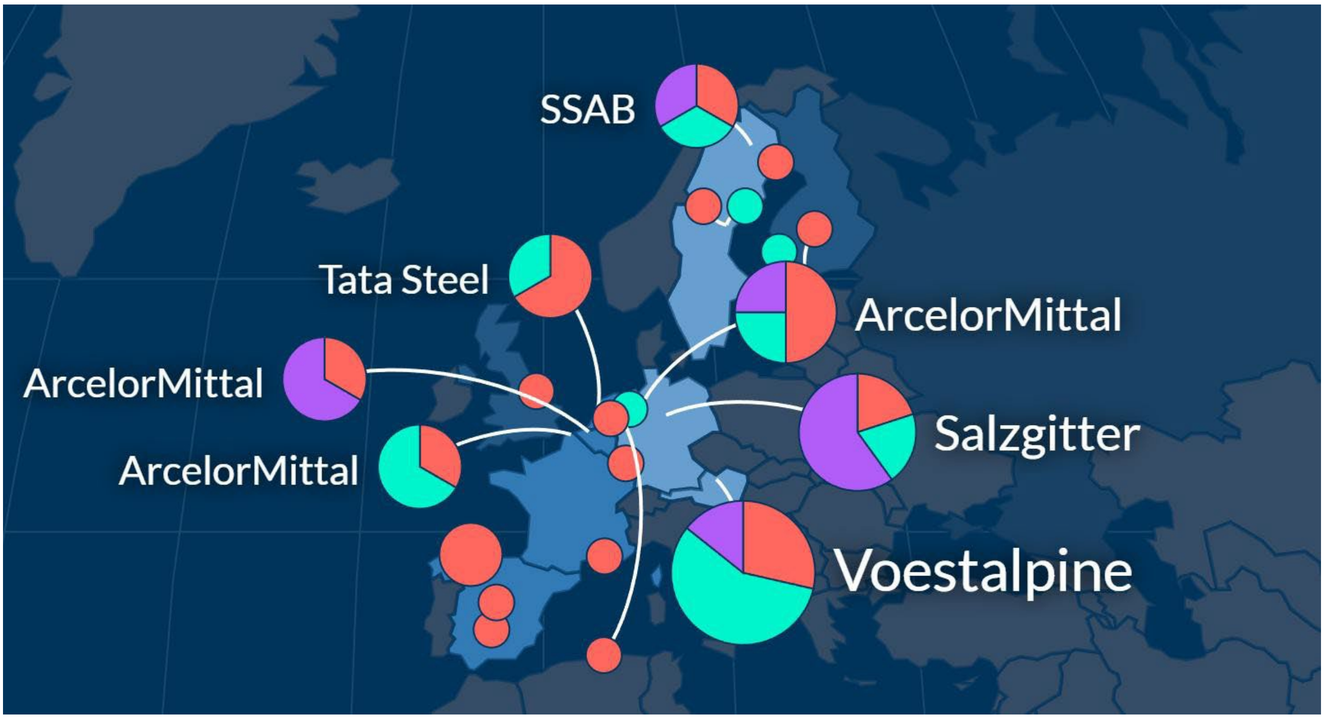


Figure 12: map of new DRI and EAF announcements in Europe 2025-2030 – this graphic from https://www.industrytransition.org/green-steel-tracker/ shows most of the sites so far reviewed

2.2.1 Low CO2 Iron and Steel Projects Worldwide

The move to low carbon iron and steelmaking is happening worldwide with the majority of large scale production facilities announced to date being based in Europe or North America.

A number of steel producers are currently building or have committed to build new 'ironmaking' factories to produce iron feedstocks from iron ores. The dominant technology that is being installed is hydrogen direct ironmaking (HDRI) with the either **Midrex** technology, owned by Mitsubishi Heavy Industries and built under licence by plant builders including Primetals and SMS, or **Energiron** technology, owned and supplied by Tenova.

Both these technologies use a vertical shaft furnace with iron ore pellets fed into the top of the furnace and direct reduced iron extracted from the bottom. Natural gas or preheated hydrogen is fed in near the bottom of the furnace and a mixture of hydrogen and steam (plus CO_2 if natural gas has been used) flows out of the top.

Both Midrex and Energiron technologies were originally developed for the reduction of iron ores using natural gas reductants and have been updated to allow the use of hydrogen as a reductant.

Some of the Midrex and Energiron plants that are already in operation using natural gas as a reductant are capable of being fed in part or fully with hydrogen reductants and some of the new plants currently under construction are intended to be able to use both natural gas and hydrogen with natural gas being phased out of use as increased amounts of hydrogen become available.

Both Midrex and Energiron plants require iron ores to be agglomerated into pellets in order to both support the weight of material in the furnace and allow sufficient gas permeability for the reductant and exhaust gases to flow around the pellets and up through the furnace. Alternative technologies where hydrogen is blown through fluidized beds of powdered iron ore have been developed in South Korea and Austria but are not in widespread use.

The phasing out of blast furnace technologies and introduction of direct ironmaking technologies is being adopted in different ways by different steel companies.

Startups, such as HYBRIT and GravityHy are developing standalone, or partnership, business making direct iron only for sale to other partners.

Some steel manufacturers are building direct ironmaking plants to replace blast furnace assets and installing either electric arc furnaces or other forms of electrical smelter to melt the direct iron and mix it with other raw materials for steelmaking.

Some steel manufacturers are replacing one of a pair of blast furnaces with a (scrap melting) electric arc furnace as a part way change to lower carbon steelmaking without yet investing in low carbon ironmaking.

Some steel manufacturers are removing blast furnaces altogether and aiming to either replicate their current product portfolio through the use of scrap steels alone or blended with iron made from iron ore from other manufacturers.

Currently operating DRI manufacturers are mainly located in North America or the Middle East and use natural gas as the reductant in their furnaces. Some of these operators are planning to move to hydrogen as the reductant as hydrogen becomes available.

An overview of the declared decarbonisation plans of iron and steelmakers in Western Europe that are due to be realised by 2030 are described below. Please note that this list is not exhaustive and for Arcelor Mittal, the largest steel company in Europe, some of the development are significantly delayed on hold due to financial and market constraints (5).

Overview of Announced Low CO_2 Iron and Steel projects and capacity in Mtpa

Announced DRI projects in Western Europe

Company	Location	DRI plant type	Capacity (Mtpa)	Target date
HYBRIT	Lulea, Sweden	Energiron	1.35	2026
Stegra	Boden, Sweden	Midrex	2.1	2026
Arcelor Mittal	Hamburg, Germany	Midrex	0.1	2026
Salzgitter Stahl	Salzgitter, Germany	Energiron	2.1	2026
TKS	Duisburg, Germany	Midrex	2.5	2027
Dillinger	Dillingen, Germany	Midrex	2.5	2028
GravityHy	Fos sur Mer, France		2.0	2029
Blastr	Inkoo, Finland	Midrex	2.0	2029
HYBRIT	Gallivare, Sweden	Energiron	1.35	2030
Tata Steel	Ijmuiden, Netherlands	Energiron	3	2030
Hydnum Steel	Puertollano, Spain	Midrex	1	2030
	Total capacity		**20**	**Mtpa**

Announced Electric Steel Furnaces in Western Europe

Company	Location	Plant builder	Capacity (Mtpa)	Target Date
Stegra	Boden, Sweden	SMS	2.5	2025
SSAB	Oxelosund, Sweden		1.5	2026
Salzgitter Stahl	Saltzgitter, Germany		1.9	2026
Arcelor Mittal	Gijon, Spain	Sarelle	1.1	2026
Voest Alpine	Linz & Donawitz, Austria	Primetals	2.5	2027
TKS	Duisburg, Germany	SMS*	2.5	2027
British Steel	UK		2.7	2028
Tata Steel	Port Talbot, UK	Tenova	3	2028
Dillenger	Dillingen & Volklingen, Germany	SMS	3.5	2028
SSAB	Lulea, Sweden		2.3	2029
Blastr	Inkoo, Finland		2.5	2029
Arcelor Mittal	Dunkirk		2.2	2029
SSAB	Raahe, Finland		2.5	2030
Tata Steel	Ijmuiden, Netherlands	Tenova	3	2030
Stegra	Boden, Sweden		2.5	2030
Hydnum Steel	Puertollano, Spain	Primetals	1.5	2029
	Total capacity		**37.7**	**Mtpa**

* Plant being built by TKS is an electric smelting furnace not an EAF.

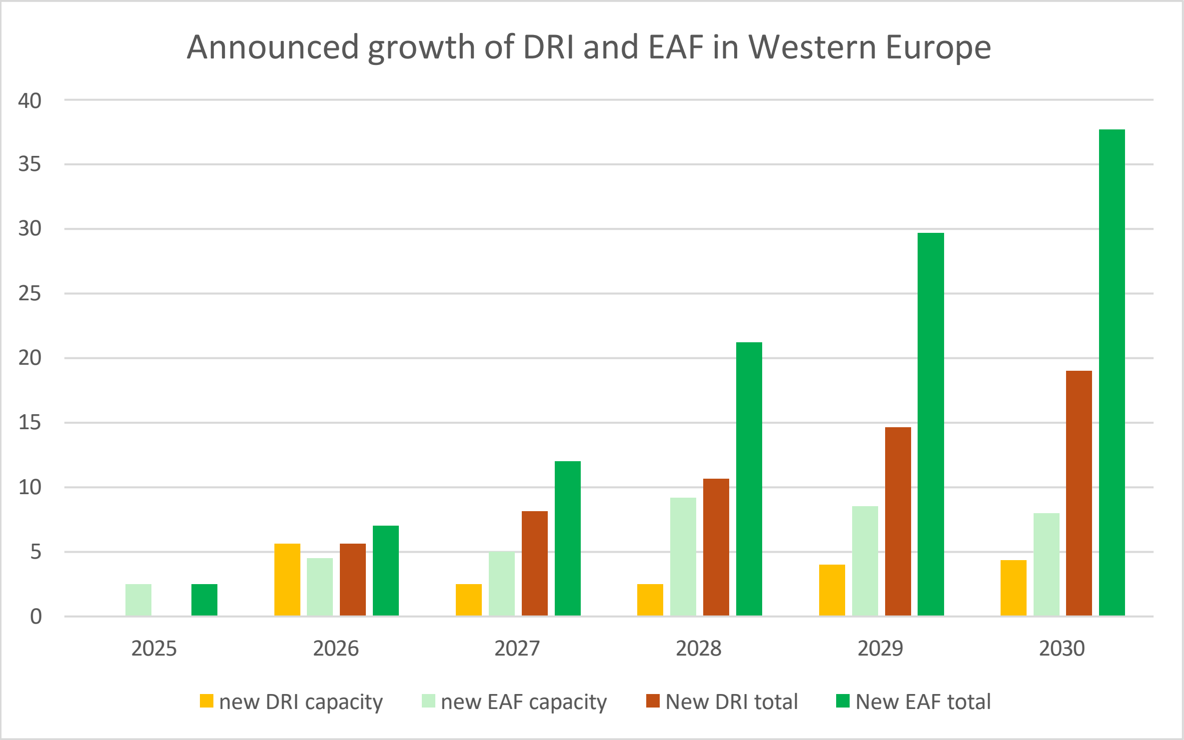


Figure 13 : New low-emission primary iron reduction (DRI) and steel melting (EAF) capacity planned in Western Europe, in Mtpa

More than 36 Mt of new electric furnace (mainly EAF) melting capacity is planned in Western Europe and just over 20 Mt of DRI capacity. **This represents a potential increased scrap demand of more than 18 Mt of scrap. This increased scrap demand will increase the price of scrap in the region and reduce scrap exports from Europe and the UK to the rest of the world.**

2.2.2 Low Carbon Steelmaking Developments

Described in Sectio 2.2.1 and Fig.13 above and summarised below is a non-exhaustive summary of low carbon iron and steel developments that have been announced in Western Europe committed to the production of steel without fossil fuels, or with very low CO_2 emissions. A significant number of these developments centre on Scandinavia and Germany but include developments in other parts of Europe including France, Spain, The Netherlands and Austria.

Stegra (formerly H2GreenSteel)

Stegra are currently building a hydrogen reduced iron plant and EAF mill with direct strip casting, at Boden, Sweden. This is a greenfield site approximately 40km from the Baltic port of Luleå (6). Stegra have announced that they will start full-scale production in 2026 intending to be the world's first commercial scale fossil-free steel company.

The plant will have the capacity to produce 2.1 million tonnes of iron per year. Some of the iron is anticipated to be used in the new steel plant being built at the same location and some will be hot briquetted for sale onto the open market as hydrogen direct reduced iron (H2DRI). Stegra's business model projects future decoupled H2DRI assets situated near cheap green power.

The iron reduction plant is using technology supplied by Midrex/Kobe Steel and hydrogen will be produced by a 700MW electrolyser supplier by Thyssen Krupp Nucera.

The company has iron ore pellet supply agreements in place with Vale, Brazil, and Rio Tinto Iron Ore Company of Canada.

Stegra are currently building an EAF mini mill steel plant in Boden, Sweden, due to start production in 2026. The plant will use a mixture of recycled raw materials and H2DRI produced onsite.

The steel plant is being built on a greenfield site and will have an initial production capacity of 2.5 million tonnes per year rising to 5 million tonnes per year by 2030.

The plant will produce both hot and cold rolled coil with the hot mill fed from a continuous strip caster.

The steel plant, caster and rolling technology are due to be supplied by SMS group.

The building of the Stegra plant, including direct iron plant, will cost €6.6 billion financed by €2.4 billion equity and €4.2 billion of debt. Stegra is part supported by €100 million from the Swedish Energy Agency fron the Industrial Leap and €285 million from the Swedish Recovery and Resilience Facility (7).

HYBRIT

HYBRIT is a joint venture between LKAB, an iron ore mining conglomerate, SSAB, a steelmaker, and Vattenfall, an energy company, aiming to make 'fossil-free' steel. It was the world's first commercial demonstration plant of this technology and will be one of the first full-scale production plants.

A demonstration plant producing 1.35 million tonnes of sponge iron from iron ores by hydrogen reduction is under construction in Gallivare in Northern Sweden adjacent to the LKAB iron ore mine. The project is part supported with SEK 3.7 Billion (€330 million) coming from EU development funds (8). The initial outlet for the iron produced is the new SSAB EAF plant at Oxelosund.

HYBRIT plan to increase production to approximately 2.7 million tonnes by 2030. This should be more than sufficient to fulfil the need for iron from virgin ores for the SSAB Scandinavia capacity of 6.1 million tonnes of steel that is planned to be online at that point.

The ore pellet for HYBRIT will be supplied by LKAB through their facilities in Gallivare. The fuels used to make the pellet are expected to be replaced by biofuels and electricity to create a fossil fuel free product.

SSAB

SSAB present a complete picture as to how they intend to offer 'largely fossil free' steel by about 2030. Involvement in the HYBRIT programme to produce low CO_2 steel through hydrogen reduction of ores has enabled them to be an early mover in the production of trial batches of low carbon steels. They have already launched brands for their low CO_2 products as SSAB Zero^{TM} and SSAB Fossil-Free^{TM} (9).

SSAB currently has 3 plants in Scandinavia that produce steel via the BF/BOS route. The blast furnaces will all be closed and the company will use hydrogen direct reduced iron produced by HYBRIT of which SSAB is a partner. This will introduce virgin iron units to the recycled steels used in their Scandinavian EAF plants. This steel will be marketed as SSAB Fossil-Free^{TM}.

They have announced closure dates for their blast furnaces at their plants in Luleå (Sweden), Oxelosund (Sweden), and Raahe (Finland).

From 2026 the BF/BOS plant at Oxelosund, Sweden, will be replaced by an EAF producing 1.5 million tonnes per year of steel. This will be followed by the replacement of their BF/BOS plant in Lulea, Sweden, with an EAF mini-mill capacity of 2.3 million tonnes and the replacement of their second EAF mini-mill plant in Raahe, Finland, with a capacity of 2.5 million tonnes per year.

Construction of the Lulea facility has now started (10) but expected completion has been delayed by approximately 1 year to 2029 due to the need to increase electricity transmission capacity to the site (11). The investment in this site is approximately €4.5 billion.

The plant in Raahe is expected to be completed in 2030.

The total steelmaking capacity of SSAB in Scandinavia will remain similar to their current capacity.

SSAB already has EAF capacity of 2.4 million tonnes per year in the USA split between plants in Montpelier, Iowa and Mobile, Alabama.

SSAB report to have delivered 50,000 tonnes of SSAB Zero^{TM} in 2023, largely produced at through their arc furnace plant in Montpelier, Iowa, and rolled at various mills. The aim is to ramp up to 1.3 million tonnes by the end of 2026, with all its plants being fossil free capable by approximately 2030.

In order to remove fossil fuels from the steel the plants will be fueled by zero carbon electricity and biofuels and process carbons removing scope 1 and 2 CO_2 emissions from their products (12).

Blastr Green Steel

Blastr Green Steel are a startup company headquartered in Norway that are planning to build a new low carbon steelmaking plant with a capacity of 2.5 million tonnes per year at the southern Baltic port of Inkoo near Helsinki in Finland (13).

The plant will feature a DRI plant feeding an electric arc furnace. It is located to take advantage of favourable energy prices in the region and a port that is accessible year round unlike those in the northern Baltic region. The plant is aiming to be operational in 2029.

Salzgitter AG

Salzgitter have mapped out a route to producing climate neutral steel across all their products by the end of 2033. They call this route the SALCOS project (14).

The first stage is to build an electric arc furnace and hydrogen direct reduction furnace and to have these in operation by the end of 2026. This will reduce the CO_2 footprint of their steel by approximately 30%. One of the companies 3 blast furnace will be retired at this point.

Tenova is the chosen technology provider and are building a 220 tonne electric arc furnace and an Energiron direct reduction furnace with a capacity of 2.1 million tonnes per year (15).

In the first phase a 100MW eletrolyser is to be installed to produce hydrogen. The DRI plant is to use a mixture of natural gas and hydrogen with further green hydrogen capacity added later.

This investment in the DRI plant is being financed by approximately €1 billion from the State of Lower Saxony and the German Federal government and over €1 billion from Salzgitter AG.

The next phase to be completed by 2030 will comprise a second arc furnace and DRI plant and the retirement of a second blast furnace.

The final phase is to commission a third arc furnace and retire the final blast furnace in 2033.

Note that although the intention to maintain a production capacity of approximately 4.7 million tonnes per year is stated the size of the operations to be built in phases 2 and 3 have not been explicitly announced.

Dillinger - Saarstahl

Dillinger Saarstahl have announced plans to reduce their carbon emissions by 55% by the early 2030s, moving 70% of their production to carbon reduced methods (16) and for their entire production to be carbon neutral by 2045.

Dillinger are building a DRI plant with a capacity of 2.5 million tonnes per year at their site in Dillengen, Germany and electric arc furnaces with a combined capacity of 3.5 million tonnes at their sites in Dillengen and Volklingen. This phase of production transformation is branded as Power4Steel and is part funded by €2.6 billion from federal and state governments. Commisioning is expected to start in 2028 and full production in 2029.

The DRI plant is to be supplied by Midrex and the arc furnaces by SMS Group (17). Initially natural gas will be used as the reductant in the DRI plant but this will be gradually mainly substituted with hydrogen as it becomes available.

Thyssenkrupp, Germany

Thyssenkrupp A.G., based in Duisburg, Germany, have a stated aim to make all their entire steel production carbon neutral by 2045 (18).

The first step in this process is to build a DRI plant, supplied by MIDREX, with a capacity of 2.5 million tonnes per year. The DRI will be fed directly into two 100MW electric smelting units with a similar combined capacity. The DRI plant will initially use natural gas as a reductant and then increase the percentage of hydrogen used as it becomes available.

The smelting units will continuously melt the DRI to produce hot-metal that will then be further alloyed and refined. The plant will produce a slag by-product similar to blast furnace slag that can be used in the cement industry (19).

These smelters are the first smelters of this kind to work at the scale of more than 1 million tonnes per year. The technology should produce hot metal with a lower nitrogen content than an EAF making the production of some steel grades easier. The slag produced will be very similar to blast furnace slag meaning that there is little change in its route market in the cement industry and the process should be capable of handling raw materials with higher gangue content than an EAF making it possible to use a wider range of iron ores.

Production is due to start in 2027 and one of the existing blast furnaces at Thyssenkrupp will be retired.

The project is being co-funded by the Federal and regional governments by approximately €2 billion with €700 million or this total from the state of North Rhine Westphalia.

Tata Steel Europe, Netherlands

Tata Steel Europe have a stated aim to reduce carbon emissions from steelmaking a the IJmuiden siteby 35-40% by 2030 and become carbon neutral by 2045 (20). The first phase is to build a DRI plant with a capacity of approximately 3 million tonnes per year and an EAF with a similar capacity. One of the companies 2 blast furnaces and one of their coke ovens will be retired at this point. The aim is understood to be to run the DRI plant using natural gas as a reductant initially and then increase the amount of hydrogen used as it become available.

The second phase of their transition will be to build a second DRI plant and electric smelting furnaces before retiring their remaining blast furnace and coke plant.

Voestalpine, Austria

voestalpine aim to reduce their carbon emissions by 30% by 2029, 50% by 2035 and fully by 2050. The first step in this process will be to build new arc furnaces at each of their sites in Linz and Donawitz with a combined capacity of 2.5 million tonnes per year by 2027 (21). Once commissioned they will retire one of the two blast furnaces at each site.

By 2035 they aim to retire both remaining blast furnaces and replace them with alternative hydrogen based reduction and electric melting facilities. The technology to be used is not yet confirmed but the company is pursuing pilot scale development of hydrogen plasma reduction technologies.

Arcelor Mittal

Germany

Arcelor Mittal have an existing direct reduced iron (DRI) plant in Hamburg, Germany, using natural gas as the reductant. The plant has a capacity of 600 thousand tonnes per year.

There is currently a companion plant being built with a capacity of 100,000 tonnes of hydrogen reduced iron per year. The hydrogen for the plant will be produced by separating the hydrogen from the exhaust gas of the existing DRI plant and using the (grey) hydrogen as the reductant in the new plant (22).

The direct reduction technology is being supplied by Midrex/Kobe Steel and the plant hoped to become the first to commercial HDRI production plant starting in 2025. The start date is now anticipated to be 2026.

Capital investment for the plant is approximately €110 million, half of which is being provided by the Federal Government of Germany.

It is anticipated that once running hydrogen supply can be changed to ‘green’ hydrogen when it becomes available.

In 2021 Arcelor announced its intention to build DRI and EAF plants at it’s sites in Bremen and Eisenhutenstadt to produce up to 3.5 million tonnes of steel per annum (23). This project was paused in November 2024 (5) and in June 2025 announced that due to a lack of market certainty it would not continue with this plan and would cancel/return grants of approximately €1.3 billion from federal and state governments (24). The company stated that it would continue with detailed planning for the construction of EAF furnaces at these sites.

Arcelor Spain

Arcelor Mittal are due to invest €1 billion in a 2.3 million tonne per year capacity hydrogen DRI plant in Gijon, Spain. The original plan was for plant to be in production before the end of 2025 and environmental approval for the plant was granted by the Asturias regional government in January 2024. The application having been made to the government on 20 December 2022 (25).

Following the Arcelor announcement in November 2024 it is understood that the project is on hold (5).

Arcelor have placed an order for an EAF furnace with a capacity of 1.1 million tonnes per year for their Gijon plant (26). This is understood to be planned to use a portion of the DRI that will be produced at the same location.

Arcelor aim for their existing arc furnace plant in Sestao, Spain, to become the worlds first zero emissions plant by 2025. Feedstock will change to HBI from Gijon (250km West) with all renewable electrical power input and sustainable biomass or other carbon neutral fuels to replace fossil fuels. The plant has a capacity of 1.6 million tonnes per year.

Arcelor France

In February 2022 Arcelor announced €1.7 billion investment at Dunkirk and Fos sur Mer to build 2.5 million tonne green Hydrogen DRI furnace and 2 electric furnaces at Dunkirk and and electric furnace at Fos sur Mer. Expected to be operational by 2027 phasing out 2 BFs at Dunkirk and 1 at Fos. Partnership with Air Liquide.

In November 2024 these projects were announced to be ‘temporarily postponed’ due to market conditions and uncertainty over CBAM.

In May 2025 Arcelor announced that it would invest €1.2 billion in and EAF at Dunkirk (27) with an estimated capacity of 2.2 million tonnes per annum (28).

Note that due to the uncertainties with the timing and execution of Arcelor Mittal DRI investments they have not been included in the table of planned capacity by 2030. The new EAF furnaces in Gijon and Dunkirk have been included in this table.

GravityHy

Based in Fos sur Mer, France, GravityHy aim to build a plant to produce 2 million tonnes per year of hydrogen reduced iron briquettes (29). The project has a total value of €2.2 billion and is due to start production in 2029 (N.B. start date has slipped from earlier 2027 aim).

In March 2025 GravityHy announced that they had €60 million of capital to start basic engineering with final investment decisions expected in 2026 (30).

The plant will use an electrolyser of approximately 700MW capacity and have and electricity supply agreement in place with EDF energy.

Iron ore supply agreements for the plant are in place with Rio Tinto Iron Ore Company of Canada.

GravitHy aim to replicate this business model at other locations once proven at Fos sur Mer, France.

HyIron

HyIron are developing a rotary furnace technology for the reduction of iron ore using hydrogen. They have a pilot plant in Lingen, Germany and are currently in the later stages of building a small production facility in Oshivela, Namibia.
The plant at Oshivela is powered by an on site solar farm and electrolyser and aims to have an initial capacity of 15,000 tonnes per year. Although small scale the company hopes to increase to megaton scales by adding further reduction modules to the plant (31).

GreenIron

A new entrant to the European H2DRI market is Swedish startup GreenIron, who have an alternative hydrogen DRI technology to the continuous shaft furnace: a modular (5 tonne x 1 hour) batch process launched at commercial scale in 2024 based on a 5 tonne per hour (30,000 tonne per year per module) reactor module plus electrolyser and heat recovery. The technology is scalable depending on hydrogen or grid electrical availability and growth of demand. GreenIron plan for 200 furnaces to be installed in the next 5 years claiming this would save the equivalent of 3% of Sweden's CO_2 emissions. GreenIron are currently proposing a build and operate 'green iron as a service' model which is also capable of recycling (reducing) millscale and mine tailing wastes. This technology is targeting incremental use of H2DRI with a variable power load, and a feedstock change which is in theory possible hour to hour. Production can be on- or off-line within 1 hour, and although it uses pelletised feedstock in order to maintain permeability in the reduction basket, it does not require energy intensive 'hot pellet' (i.e. bonded at high temperature for strength) which can be necessary for conventional DRI production in a shaft reactor.

Hydnum Steel

Another new entrant, planning to open ‘the first green steel mill in Spain’ with an initial capability of 1.5 Mtpa in 2029 rising to 2.6 Mtpa in the 2030s. Recycling steel for direct strip casting using EAF with H2DRI to supplement and a significant water efficiency focus. Partners include Russula, Primetals and Siemens

POSCO Steel

POSCO Steel in South Korea are piloting HyREX, a hydrogen transition of their established FinEX direct reduction technology co-developed with Primetals, utilising cascades of fluidised bed reactors and a melting unit, which between them reduce and melt liquid iron directly from powdered iron ore without the need for a pelletisation stage. A 1MT demonstration unit is planned to come onstream in 2028 followed by commercialisation in the early 2030s

Advantages of twin investment in DRI + EAF

1. Security of supply of Fe units – particularly given that a typical ratio of planned DRI capability to overall melting capability is 1:3 suggesting that Fe units from DRI will be balancing out availability of scrap, and not just diluting it to hit quality requirements, once Europe’s anticipated 25-30MT of extra scrap demand eventuates
2. Control of embodied carbon – or at least control of the validation and potential rebates, depending on the source of electricity supply for electrolysis (or gas for DRI or cracking to produce hydrogen). Electricity grid carbon intensity varies significantly within Europe. Some steelmakers are therefore also linked with major renewable power construction projects in order to guarantee a captive green energy supply.
3. Peak hydrogen production by electrolysis, and preheating for the DRI reactor, and peak steel melting at minimal electricity price periods
4. Control of value in use of the solid DRI product via optimising the degree of metallisation

DRI-EAF Direct feed

Some developments, particularly where DRI+EAF is replacing a blast furnace as a reduction and melting unit, will employ a direct hot link between DRI output of reduced iron pellets at a nominal 700 °C and the EAF which will be melting its DRI and/or scrap feedstock at a nominal 1600 °C. This ensures thermal efficiency of the system and also mitigates the need for cooling, passivation and storage, or hot briquetting, cooling and storage of the DRI between reduction and melting steps.

This approach seems most suited to steelmaking processes where a constant demand for ore based iron units is assumed

Carbon Capture from integrated steelworks (BF-BOF)

An appraisal by MPI of a recent exhaustive review of CCUS (32) (see **APPENDIX 2**) concludes that due to the mismatch between desirable CC plant operating conditions and the extreme complexity of CO_2-rich gas streams emitted and re-used around integrated steel works, CCUS is not currently an attractive option for wholesale decarbonisation of traditional steelmaking. For this reason, despite several promising pilots on a proportion of off-gas from one particular point in the system, no steelmaker has invested in the kind of site-wide solution necessary to compete with DRI-EAF on emissions and this does not feature in decarbonisation proposals currently tabled by UK steelmakers.

This conclusion, that CCUS is not a realistic avenue for wholescale decarbonisation of UK steelmaking, is corroborated by techno-economic studies carried out internally by steelmakers and other industry bodies. Assets such as gas-fired rolling mills with planned lifetimes of 10 years or more may benefit from local CCS/CCUS on a case-by-case basis.

2.3 Capex and Opex estimates for DRI iron production

2.3.1 Capex

A consistent finding for European Capex announcements, corroborated by plant builders, is a cost of approximately €1 Bn per 1Mtpa capacity of H2DRI output, divided evenly between

- the DRI reactor and its materials handling systems, and
- the hydrogen electrolysis and gas handling and storage systems

Although most DRI plants are beginning with natural gas as the feedstock and may be planning to upgrade the gas cracking unit with hydrogen heating, recovery and storage at a later stage.

Whilst economic studies on building captive DRI capability have been carried out internally by steelmakers and employee's unions, these focused on individual site requirements, which tended to fall below the 1MT cutoff for the smaller commercial DRI plant, rather than considering a single plant to service the whole UK demand.

However, whilst both major UK steelmakers transitioning to EAF production have expressed willingness to buy UK DRI 'at the right price and availability', neither has indicated a priority to invest in building and operating such a facility and third party proposals are still at early stages well ahead of FID. UK energy price is a major consideration in framing this perspective.

2.3.2 Opex

Natural gas consumption for DRI is in the order of 3,000 kWh or 10.4 GJ per tonne of iron produced, representing an annual demand of around 6TWh for a 2Mt plant.

Assuming current UK industrial gas prices of 3.75 p/kWh, a level which is receding from 2022 highs and potentially trending to pre-2021 levels of 2.5p barring further geopolitical shocks this is in a range of £112-80 of gas cost per tonne of iron, or £225-160M per year

Or (see 2.4.1.2 below) given **electricity** prices of 13.46 p/kWh () and potentially trending to 12p not accounting for market reforms, the demand for electrolysis to service a 2Mt H2-DRI plant would be in the order of 12TWh per year, with an electricity cost at current prices of £1.4-1.6 Bn

The source for these figures was "Prices of fuels purchased by manufacturing industry - GOV.UK" taking the provisional 2024 prices of natural gas for large users, or electricity for extra large users, accessed from the March 2025 update

The UK's currently high industrial energy costs for both gas and electricity are consistently cited as a negative factor in decision making around DRI plant location. Although the UK has an enviable wind resource and one of the lowest carbon-intensity electricity grids in the world, in order to compete with cheap renewable power in hydroelectric-surplus Sweden or Canada, or solar-rich Spain, South America, Australia or MENA (where there is also cheap natural gas), or baseload nuclear power in France, conversations with H2DRI investors suggest electricity costs may need to approach £25-35 per MWh (ie 2.5-3.5 p/kWh). In any event, competitive industrial energy pricing and appropriate grid reinforcement is a recognised goal for industrial policy.

DRI production is a source of skilled **employment**, with staffing levels similar to a blast furnace, employing roughly 150 trained skilled people for a DRI plant (across 3 shifts). This is separate from jobs in ore handling, blending, pelletising and other upstream activities.

2.3.2.1 Estimating of the amount of hydrogen and electrolyser size required to run a hydrogen ironmaking plant

In an ideal theoretical scenario it takes 54kg of hydrogen to produce 1 tonne of iron from ore.

If hydrogen can be used for reduction with an efficiency of 90% (ie 90% of hydrogen produced and recycled around the furnace is eventually consumed by reduction) then it will require 60kg of hydrogen to produce 1 tonne of iron, equating to approximately 2000 kWh of hydrogen. With electrolyser efficiencies expected to approach 75% by 2030 this will require 2600-3000 kWh of electricity per tonne of iron, ie around £425 electricity per tonne of H2DRI iron at current UK prices.

To produce 1 million tonnes of iron will require about 60,000,000 tonnes of hydrogen (200 tonnes per day).

A 1 MWe electrolyser can produce approximately 150 tonnes of hydrogen per year. Review of emerging techniques for hydrogen production from electrolysis of water page 31).

A million tonne H2-DRI steel plant would require approximately 400MWe electrolyser i.e. an electrical energy demand for the electrolysis alone in excess of 3GWh per year

Assuming greater efficiency can be gained with very large electrolysers this correlates with Stegra, GravitHy and TKS who are both planning to build 700 MW electrolysers to feed an ironmaking capacity of 2.1 to 2.5 Mtpa.

2.3.3 Infrastructure requirements

Feedstock – iron ore

A DRI plant typically comprises a gas handling plant (whether hydrogen or natural gas) and vertical shaft reactor, plus feedstock from pelletised iron ore. The pellet plant may be integrated or separate from the DRI plant and comprises a similar set of requirements to a blast furnace pellet plant, i.e. upstream assets of an ore terminal, ore crushing and grinding, beneficiation (concentration of iron-rich fractions of the ore), blending, and a pelletisation plant. Current practice uses a 3-400°C hot bonding method in order to impart sufficient handling strength to the DRI pellets but pellets tend to be stockpiled and charged cold to the furnace where they receive pre-heating before entering the 950°C reaction shaft.

Feedstock – natural gas supply, hydrogen generation or supply

The typical demand for natural gas or hydrogen for DRI is detailed in section 2.4.1 above. Either feedstock will require some storage buffer capacity. In the case of natural gas this would simply be in order to guarantee safe and stable operation of the gas plant and shutdown in the event of gas network failure. In the case of hydrogen, storage must also buffer the electrolysis units and allow for optimisation of peak electrolysis during off-peak electricity tariffs or similar demand-side control agreements with the electricity supplier.

Electrical supply

The scale of electrical supply for a DRI site will depend on whether electrolysis for hydrogen (and oxygen) production is required – see section 2.4.2 and note that power in this case is on the scale of several gigawatts, as is that of a large EAF melt shop, requiring extensive grid reinforcement and creating opportunity for tied renewable energy supply. Some large industrial sites including steelmakers are pursuing co-investment or supply agreements directly with renewable energy developers or asset owners (hydroelectric, wind or solar) or small modular nuclear reactors (SMR) for this reason.

Aside from electrolysis, electrical power is needed for heating the reaction gas (although gas DRI will tend to utilise gas for much of its preheating requirements), gas pressurisation and movement, water cooling and pumping, emergency systems and general site power.

Transport links, site footprint and pelletisation plant

As mentioned above, a typical plant comprises a tall vertical shaft furnace which has a similar footprint to a blast furnace and can be sited close to or even directly above an EAF or ESF in order to utilise hot feed of the solid pellets of DRI (at 800°C) directly to the steel melting furnace. If this option is not pursued, and DRI is to be transported off site for later use, there will be a requirement for cooling bays, allowance of several days residence for passivation (surface oxidation to a small degree to reduce the potential for oxidation, self heating and creation of fire risk during transport. Shipping transport of hot briquetted iron (ie DRI which is compressed into briquettes of a few kg each while still hot and malleable) is much preferred, for this reason. In any event, DRI is transportation is generally supported for safety reasons with nitrogen purging

Hydrogen DRI is not known to experience any additional problems with regards passivation, although the lower density compared to NG-DRI is leading to efforts to reassess the minimum density requirements in the shipping regulations.

There will clearly be a requirement for DRI sites to be managed as top tier COMAH if they are not already part of an existing COMAH site such as a steelworks.

Other site footprint will be dependent on the integration or separation of ore processing and pelletisation assets but as a minimum will require handling and conveyor transport for several thousands of tonnes of DRI pellet per day. There is an operational energy gain (5-10%) of being able to hot charge 'fresh' DRI into an EAF

Since all iron ore is imported to the UK, enhanced transport links with shipping ports is a consideration, as is the establishment and reinforcement of reliable bulk transport (rail links) for scrap metal flows, since in most cases these will make up the majority of the feedstock for the new EAF assets being constructed in the UK.

Should a new pelletisation plant be constructed in the UK, it may be safer and more economical to transport pellet by rail or sea to DRI asset(s) located close to EAF melting, or to hot briquette any DRI produced at the same location into HBI for transport, rather than to transport bulk DRI off site, since it is subject to more stringent regulations (33).

2.3.4 Recommendation: feasibility studies

It is recommended that (dependent on mechanisms to cut, rebate or guarantee lower energy prices) a detailed feasibility study be carried out for a single national hydrogen-ready 2Mt NG-DRI plant (incumbent vertical shaft furnace technology) which can fully decarbonise the feedstock, act as some inertia on the grid (ie increase productivity during surplus renewable energy events) and integrate with ports, and domestic transport links to follow scrap routes to steelworks. It should incorporate previous single-offtaker studies where possible.

This study should be accompanied by a parallel feasibility study for scaleable modular technology, with recommendations if applicable for fast tracking innovation in order to build a national 'distributed' ironmaking capability, i.e. one which grows organically with the power and hydrogen grids.

Both studies should include realistic timelines to full green ironmaking operation

SECTION 3 - SUPPLY

After energy prices, security of iron ore supply is the most significant issue for primary iron capability

Section 3.1 - Assessment of associated developments in the primary iron supply chain, i.e. the changing quality of available ores and the evolution of ore suppliers to green iron suppliers

Section 3.2 - Assessment of related supply chain impacts of choices in ironmaking – eg in value chain for steelmaking slags, utilisation of wastes

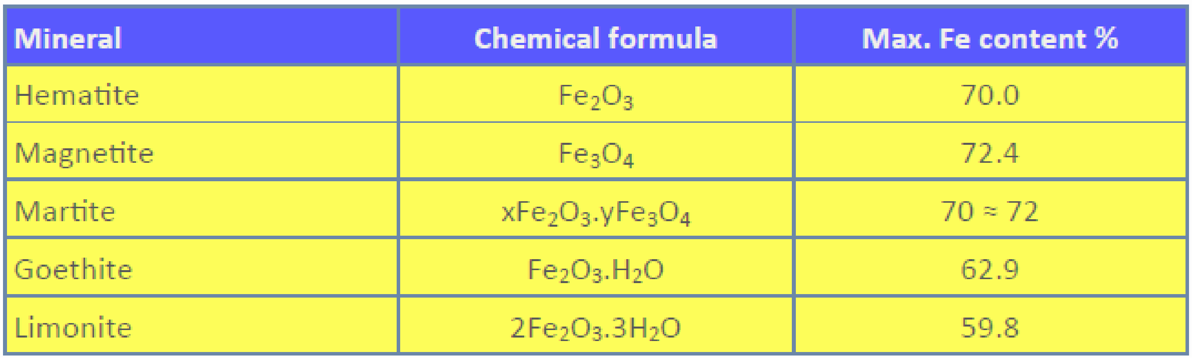
3.1 Primary iron supply chain evolution

3.1.1 Briefing: Iron ore (Source: International Iron Metallics Association)

Fact sheets available on www.metallics.org (34)

Relevance of Iron Ore to Ore-Based Metallics (OBMs)

- Iron ore is the fifth most abundant element in the earth's crust.
- Global resources of iron ore in 2017 were estimated by the USGS at more than 800 billion tons, containing 230 billion tons iron.
- Production of iron ore in 2017 was estimated by USGS at 2.4 billion tons with 1.5 billion tons Fe content.
- The most significant suppliers of iron ore to the global market in 2017 were Australia and Brazil with a combined market share of >50% in terms of production. Other important producer countries included China and India.
- In terms of cross border trade, Australia and Brazil accounted for almost 80 % of the total volume of about 1.6 billion tons.
- Between them, the four major producers Rio Tinto Iron Ore, BHP, FMG and Vale accounted for just over 70% of cross border trade in 2017.



Mineral	Chemical formula	Max. Fe content %
Hematite	Fe_2O_3	70.0
Magnetite	Fe_3O_4	72.4
Martite	$xFe_2O_3.yFe_3O_4$	70 ≈ 72
Goethite	$Fe_2O_3.H_2O$	62.9
Limonite	$2Fe_2O_3.3H_2O$	59.8

Briefing: Iron ore production steps

- Pre-mining: stripping, drilling, blasting.
- Mining: iron ore is generally mined in open pits although there are underground mines, notably in Sweden and China.
- Beneficiation: direct shipping ores, i.e. those with sufficiently high Fe content (at least 55-58% Fe), require only crushing and screening to produce lump ore and sinter feed fines.
- Concentration: lower grade ores need additional beneficiation steps to achieve acceptable Fe content, whereby the iron oxide minerals are liberated through grinding and separated from the gangue by gravity separation, magnetic separation or flotation to produce iron ore concentrates.
- With very fine concentrates, agglomeration is required to render them suitable for use in ironmaking processes (the BF or DR shaft burden needs to be permeable enough to enable even gas flowthrough it which would not be the case if fines or concentrates were charged directly to the furnace): pelletizing is the most common method of iron ore agglomeration where the product has to be handled and shipped over long distances, due to the greater physical strength of pellets in com-parison with sinter. Except for a few cases, sintering takes place adjacent to the blast furnace.

Briefing: Types of iron ore

- The most commonly used type is Iron Ore Fines (generally known as Sinter Feed) which is sintered at the receiving steel mill, prior to being charged to the blast furnace. Iron Ore Fines typically have particle size up to 6.3 mm. Fluidised bed direct reduction processes use Iron Ore Fines as their feedstock.
- Having been ground, Iron Ore Concentrates are finer than sinter feed with a particle size in the range below 2-5 mm and are used as feedstock for both sintering and pelletizing (sometimes re-grinding is required to produce pellets).
- Even finer still is Pellet Feed which has average particle size <75 µm with a significant proportion>45 µm and a high specific surface area.
- Iron Ore Lump, a direct shipping ore is typically sized between 6.3 and 25-30 mm and is charged directly to the blast furnace, usually after screening. Iron Ore Lump is a also a primary feedstock material for production of sponge iron in rotary kiln furnaces in India and certain high grades are also used in gas-based shaft furnace direct reduction plants.
- Iron Ore Pellets typically have particle size distribution of 9-16 mm with a high compressive strength and resistance to abrasion. Due to the possibility to blend various additives with the pellet feed, e.g. limestone, dolomite or olivine, pellets can be both acid and basic in terms of their chemistry. The majority of pellets are used in blast furnaces (BF grade), but certain grades of pellets, with high Fe content (≥ 67%) and low acid gangue content (≤ 2%), (DR grade), are the main feedstock for production of DRI in gas-based shaft furnaces.

Figure 14: (L-R) top row = ores: DRI pellet, Lump ore, sinter fines (crushed ore), concentrate; (L-R) bottom row = metallics: DRI, HBI, pig iron, GPI

- Chemical analysis of iron ore: relevance to OBMs and EAF steelmaking
- Pig Iron: the blast furnace is a flexible chemical smelting reactor and many unwanted impurities will report to the slag. However, certain impurities, such as phosphorus and part of the sulphur, will carry through to the liquid iron and hence the pig iron, so careful selection and control of iron ore, coal/coke/charcoal raw materials is essential to achievement of the desired pig iron analysis.

- DRI and HBI: the direct reduction of iron ore is a solid state reaction, so apart from oxygen, what is fed to the DRI plant is contained in the DRI product, including gangue components and impurities. Thus, careful raw material selection and control is critical to the achievement of the required DRI and HBI analysis. High reducibility results in high metallization of the iron ore feedstock and is important to minimise the content of residual unreduced iron oxides entering the EAF since they require extra chemical energy to reduce, or will simply add to the slag volumes.

3.1.2 Decarbonizing Steel in Countries without Iron Ore

3.1.2.2 Concept of “Green Iron Corridors”

A report published by the Rocky Mountain Institute (RMI) in September 2024 (35) evaluated the status of Europe and North America as net importers of iron ore, combined with a growing need to decarbonize steel production. RMI concluded that this leaves the regions with three pathways to meet their green steel demand goals:

Option 1: Importing iron ore and domestically producing green hydrogen, green iron, and steel.

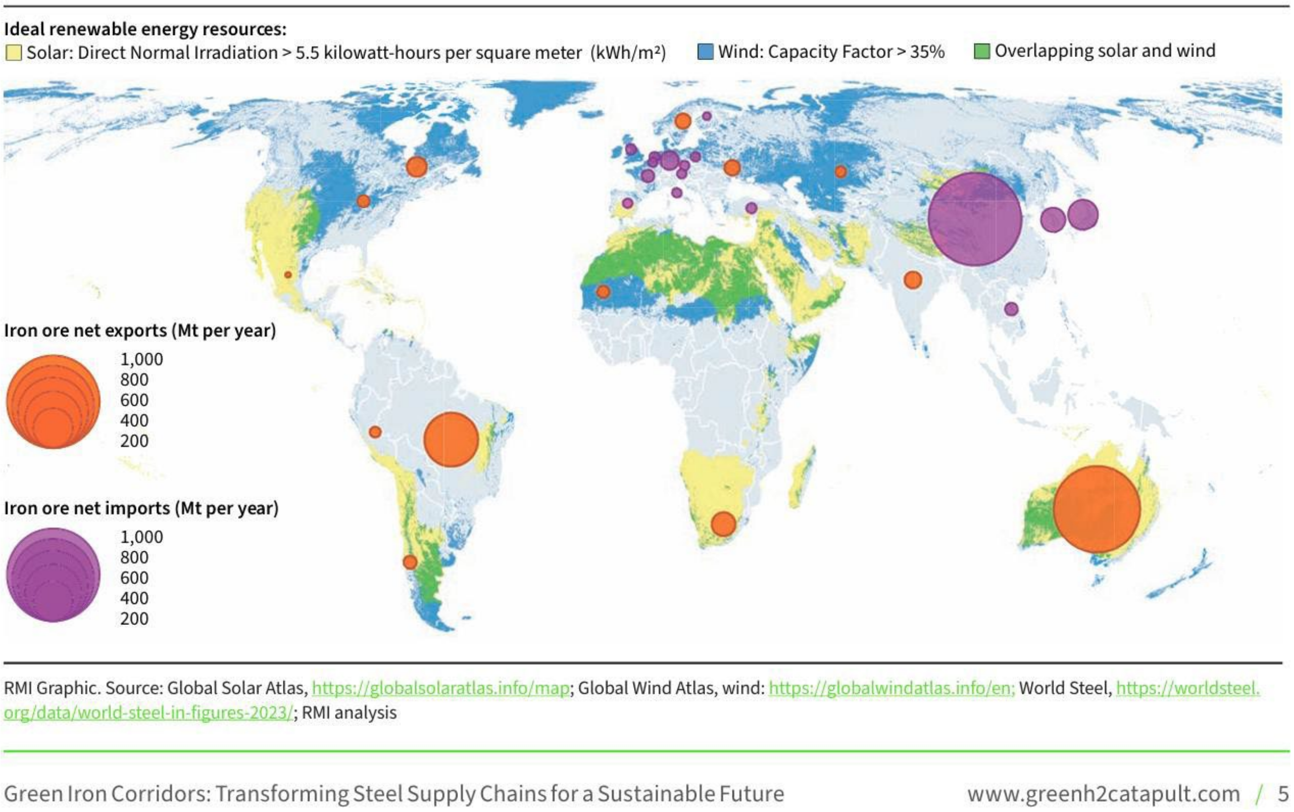
Option 2: Importing iron ore and green hydrogen for domestic production of green iron and steel.

Option 3: Importing green DRI/HBI for domestic production of steel.

RMI and the Green Hydrogen Catapult carried out a global systems-level assessment of current iron unit exporters (ore, pellets, DRI and HBI) and their existing customers (steelmakers) in Europe (including the UK) and North America. The potential of import and export contenders was evaluated against an assessment framework developed by RMI and the Green Hydrogen Catapult that includes technical, economic and geopolitical criteria. The report defined the opportunities and challenges that are present now and likely to develop in the future on the supply and demand for virgin iron units and made recommendations to help develop robust supply chains, “Green Iron Corridors”.

When considering the use of H2DRI in the steelmaking process, it must be noted that up to 50% of the final steel cost comes from the green hydrogen for the ironmaking step, so the cost-competitiveness of steel will be driven by the availability, pricing structure and scalability of renewable energy. As cost-competitive green hydrogen will play a significant role in the global energy transition beyond just steel, countries are establishing hydrogen import and export strategies, depending on their resources and needs. Regions such as Northern Africa and Australia are emerging as promising green hydrogen exporters due to abundant solar energy resources in low population density ore-producing regions (i.e. low competition for energy between industry and civilisation). Others will rely on imports of hydrogen to supplement their domestic production capabilities, such as the EU Hydrogen Strategy target of importing 10Mtpa of green hydrogen by 2030. Significant imports of green hydrogen could also be faced by the UK, if domestic green hydrogen production does not match demand.

When these hydrogen export and import regions overlap with existing iron ore supply routes, transporting green iron is both more cost effective and saves energy compared with transporting hydrogen and ore separately. It could prove beneficial to split up the steel production processes with ironmaking in locations with abundant ore and accessible renewable energy, and steelmaking in locations that have strong manufacturing capabilities and demand already in place (Figure 16). The authors refer to these potential export–import routes as “Green Iron Corridors”.



RMI Graphic. Source: Global Solar Atlas, https://globalsolaratlas.info/map; Global Wind Atlas, wind: https://globalwindatlas.info/en; World Steel, https://worldsteel.org/data/world-steel-in-figures-2023/; RMI analysis

Green Iron Corridors: Transforming Steel Supply Chains for a Sustainable Future www.greenh2catapult.com / 5

Figure 16: "Green Iron Corridors" separate ironmaking and steelmaking processes: Ironmaking located with abundant ore and renewable energy. Steelmaking in other strong manufacturing regions with existing reliance on iron ore imports.

The report presented three case studies to demonstrate:

1. How policy can drive supply and demand in North America and Europe .
2. The challenges and opportunities for emerging economies on the supply side, with the example of Mauritania
3. Nuances of iron ore beneficiation to control/improve iron unit inputs to feed H2DRI production, with the example of Australia

These case studies were used to describe the emerging green iron landscape and to suggest the next steps required to advance the "Green Iron Corridors" concept.

3.1.2.3 "Green Iron Corridors" – Potential Global Benefits

RMI and the Green Hydrogen Catapult believe that "Green Iron Corridors" can offer significant benefits along the virgin iron supply chain including cost savings, increased efficiency, CO_2 emissions reductions and economic opportunity for both importing and exporting countries.

1. Iron ore quality will not constrain shifting to the direct reduction of iron (DRI) in the next decade. A combination of utilizing high-grade ores, upstream beneficiation, and downstream smelting technologies will pave the way for the transition. Easier-to-upgrade magnetite ores will be prioritized for the first wave of pellet production. Hematite ores that are more difficult to upgrade will rely on collaboration along the supply chain to optimize the amount of beneficiation versus downstream process adjustments (via the DRI, smelter, or electric arc furnace [EAF]) in order to avoid unnecessary iron losses. In the long term, as costs for renewables and hydrogen decline, additional smelting steps for low-grade ores will become more cost-effective.

2. Green iron trade can allow traditional steelmaking countries to maintain large parts of their skilled workforces into the future, given that up to 75% of the sector's direct jobs sit downstream (associated with steelmaking and manufacturing). However, it will be critical to plan for workforce transition support on a subregional level, as changing trade patterns will influence how countries decide to move in the value chain.

3. Restructuring half of primary steelmaking to use green iron could save >$25 billion annually across the 10 highest priority importers at today's prices. This translates to savings of $80–$125 per tonne of steel due to the higher capacity factors in the exporter regions, which reduce the needed renewables build-out by 20–50 gigawatts (GW). The additional re-heating required for green iron after transport is small, representing only ~3% of the total steelmaking energy, and is partially offset by lower transport energy due to the reduced volume compared with transporting iron ore.

4. First mover producers and buyers, coupled with strong policy support, will drive initial green corridors by incentivizing supply in export candidate countries through hydrogen and renewable energy subsidies, working in tandem with import candidates that have strong demand-driving policies such as mandates and carbon pricing. International collaboration alongside specific green iron targets will be necessary to fully realize these policy benefits.

5. Emerging economies possess strong opportunity to move into this market given their resource endowments, which ultimately will position them as cost-competitive producers. Measures to mitigate risks and reduce the cost of capital are needed to support project deployment at scale. Multilateral development banks can play a role in reducing financial barriers and developing the required infrastructure to support these promising exporting contenders. A strong emphasis on accountability must be placed on emerging trade relationships and agreements to avoid extractive relationships and ensure that sustainable industrial activities thrive in these regions.

6. Fast-tracking corridor opportunities between existing and emerging iron exporter regions to the EU and Asia could abate an annual ~30 million tonnes (Mt) CO_2 by 2030 (>50% of Germany's steel sector emissions today). Of the 50 importer/exporter options evaluated, more than 10 key corridors emerged as high contenders. Paving the way for global green iron trade will require bilateral political action to recognize the net benefits.

3.1.3 Indirect supply chain issues

When considering the current synergies between primary ironmaking and the life cycles of steelmaking by-products, it is worth noting that blast furnaces produce between 200-400 kg of molten slag for every tonne of hot metal, equating to around 1Mt per year from a 3Mt steelworks. If granulated by rapid water quenching soon after it is tapped from the blast furnace, the product can be ground to powder and sold at a premium similar or above that of ordinary Portland cement, as ‘ground granulated blast furnace slag’ (GGBS).

The reason for this serendipitous by-product’s desirable qualities are connected to the balance of ‘gangue’ elements melting out of the iron ore (silicon dioxide, aluminium oxide) and calcium oxide from the limestone added as a flux to the furnace.

Such a balance is not directly replicated in EAF melting – electrical steelmaking slags are generally of very low value, and arise in much smaller volumes since the furnace feedstock is generally much higher in iron and lower in any other elements than blast furnace feedstock. The focus on high iron yield from the feedstock also leads to a strong preference and economic advantage to low-gangue ore-based metallic additions. Pig iron has already had its gangue elements recovered as slag; DRI/HBI are for this reason centred on the premium end of the iron ore market, targeting iron contents of 68% and above, and they yield relatively little slag.

However – two developments are worth noting since they open up the possibility of cheaper, lower iron-content ores becoming viable for Dri and EAF steelmaking:

EAF slags as cement substitutes

A number of R&D programmes are ongoing to optimise the re-use value of EAF slags – it is beyond the scope of this review to go into any detail other than to mention two recent initiatives: European programme EUROSLAG and a UK programme Cement 2 Zero which demonstrated recycling of demolition waste cement through the EAF to regenerate a cement clinker product which is undergoing commercialisation as ReClinker.

Electric Smelting Furnaces

Covered in more detail in Section 2.1.7, ESF’s are an open bath melting and reducing furnace similar to blast furnaces in the sense that they create a relatively acidic floating slag layer which can be tapped off separately to the molten iron, and therefore improve on the economics of making steel from lower iron (higher gangue) ores since there is no gangue carry-over to the EAF, and the slag itself can be granulated and sold in a similar manner to GGBS, thus recovering some of the market lost with the closure of a blast furnace.

SECTION 4 - CONCLUSIONS AND OPTIONS

4.1 Conclusions – the demand for primary iron and the degree of importance and urgency for the UK steel sector

On the opening ‘return to business as usual’ scenario, assuming 2022/23 BF-BOS order books are covered by domestic EAF production by 2028, aggregate demand for primary iron (aka virgin iron, ore-based metallics), will be between 1-1.5 Mt per year, mainly as a supplement for 6Mtpa of new scrap melting in Port Talbot and Scunthorpe (Based on previously published plans. At the time of writing no final decisions have been made into investment at British Steel, Scunthorpe). Existing arc furnace operators’ expectations (in S. Yorkshire and Cardiff) are currently adequately served by the domestic scrap market or specialist alloy supply chains.

A ‘UK Steel Max’ scenario akin to the vision of the UK Steel Strategy consultation green paper, with doubled capacity serving established domestic markets and new capability for defence and for 1-2 Mt wide plate for offshore wind fabrication, will utilise most of the domestic scrap arisings and even then will require an additional 2–3Mt primary iron. At this level, dependent on the scrap supply volumes and quality it is possible that primary iron will be necessary to meet the overall demand for iron units as well as for steelmaking optimisation, ie demand could reach 5Mtpa.

Note: the aspiration for domestic production of steel plate for off-shore wind will itself require specific investment support since new plant will be required to meet modern size requirements.

Importance is High

Availability of some form of primary iron is of **high importance** for certain strip and long construction products in order to dilute unwanted residual content in scrap and to control nitrogen levels. The only substitute would be extremely high quality scrap feed coupled with longer processing times and carbon additions for slag foaming

It is also of **medium importance** as a means of efficient **carbon energy** transfer to the EAF to enable steelmaking efficiency. The alternative would be increased use of injected carbon as pulverised coal/coke, or biocarbon (unavailable in bulk), and increased use of electrical or gas energy for maintaining furnace temperatures

Security of supply must be assessed should international ‘green iron corridors’ be seen as the most reasonable way forward, although it should be noted that the UK has been importing all its primary iron ore along broadly the same trade routes for some decades.

Coupled with the urgency factors below, and the question of national sovereignty, acquisition of low emission domestic iron making capability should be considered of **medium-high importance**

Urgency is medium to high

This demand can be met by imported blast furnace pig iron, imported or domestically produced DRI or HBI.

The issue of **availability** is of **medium urgency** as all three commodities are currently available on international markets and/or via parent companies, and production of them all is expected to increase globally before 2028; however, much of the new DRI capacity is captive capacity serving existing steel mills in order to displace BF hot iron, and availability is likely to be constrained until the mid 2030's, exacerbating the increased demand for high quality scrap across Europe. This tends to the conclusion that dilution will be most easily achieved in the first instance (2027-2030) by steelmakers using imported blast furnace granulated pig iron (GPI)

The issue of **embodied carbon** content in primary iron is also now of **medium-high urgency** since market demand for and supply of 'green' steel designations is accelerating globally, and requires NG-DRI or H2-DRI if it is to be used in dilution factors of 25% or more and still qualify as 'green steel'. Blast furnace GPI dilution of scrap is not a long term path to full decarbonisation. The immediate short term solution for UK steelmakers to address this by use of pig iron will satisfy the need to meet steel quality requirement and should avoid short term supply imbalances for DRI supply but looks likely not to meet the more exacting medium to longer term market aspiration for decarbonised steel.

For this reason the acquisition of low-emission iron reduction capability should be considered to be at least **medium urgency** for the UK under any scenario with production aiming above a restoration of business as usual.

A major challenge in this is UK energy cost competitiveness which remains a significant barrier to investment and production, whether for DRI manufacture or EAF steelmaking.

4.2 Options - technology options and choices in the context of regional and global developments

a) Import option (Currently the assumed default without intervention)

Each steelmaker buys the optimum quality of scrap domestically as their main feedstock and imports GPI, or HBI as needed to dilute scrap for their orderbook (a calculation based on cost, quality and carbon content). Option of importing low emission / green HBI if customers specifically require a low embodied carbon product.

Technology choices will require

- R&D to develop appropriate confidence in steelmaking (process, grades) and to continue to decarbonise downstream processes.
- Scrap processing upgrades (e.g. to 'supershred') to guarantee the volumes of high quality feedstock
- Electricity and gas price reductions to enable competitiveness with decarbonising European suppliers

Domestic production options:

b) DRI 1 or 2MT furnace – Midrex or Energiron

A single DRI facility, most likely operating adjacent to an established steel production site to enable hot connect efficiencies, but supplying sufficient volumes (1-2 Mtpa) of DRI or HBI to service most of the primary iron needs of the domestic sector up to and including the 'UK Steel Max' scenario. Running at reasonable capacity factor, this plant would represent a significant semi-flexible point load on the energy grid as a variable continuous process, but one capable of coming rapidly on and off line if necessary (unlike a blast furnace).

The technology choice will require the same key points as above (R&D support, scrap, energy price) plus

- Would require a natural gas supply in the order of 6TWh per year
- Commitment and investments support to transition to blue or full green hydrogen DRI:
    - As national generation and storage capacity develops to supply 120,000 Tonnes (12TWh)
    - or via captive electrolysis and storage.
        - Likely some ongoing demand for hydrocarbons (20% NG or biogas) to retain some dissolved carbon in the DRI in order to optimise steelmaking performance
- 1.5-3Mtpa Ore import, handling, blending and pelletisation plant on site or on a reliable transport link
- Footprint analogous to blast furnace plus power station
- Staffing analogous to a blast furnace plus pellet plant (200 people)

c) Distributed or modular DRI – GreenIron or similar

Clusters of modules each batch producing 30,000 Tpa (5 tonne per hour) of hydrogen reduced iron with tied modular electrolysers, could be built closer to individual demand sites, added to sequentially over several years as grid capacity, electrolyser costs or delivered hydrogen capacity reduces. Very dispatchable, i.e. can stop production or change feedstock within an hour. Total UK primary iron demand would require 50-100 modules, potentially in 3-4 clusters in different parts of the country, but the scalability (in 30kT increments) offers more flexibility than a single '1MT or 2MT' DRI unit. A six-module cluster could supply a 10%, zero CO_2 DRI feed to a 300 Tonne per hour EAF. Also able to reduce partially with natural gas for a carburised DRI, and potentially capable of recycling iron oxide millscale and similar oxide wastes back to metallics.

The technology choice would likely complement rather than completely replace imports but could provide a lower capex bridge to full decarbonisation, and/or a reduction route for smaller materials streams.

- Would require significantly lower electricity costs and hydrogen costs than currently experienced in the UK, in the order of £30/MWh. In discussion GreenIron regarded this as the major barrier to uptake in the UK.

Future horizon

DRI coupled with Electric Smelting technology looks likely to increase in prominence from 2030 onwards, producing low emission hot metal (ie molten pig iron equivalent)

Fluidised bed reduction, direct plasma reduction, and electrolytic reduction all hold promise for cost and operability improvements in the 2030s but should be seen as part of a technology watch list (which should include significant R&D support) rather than immediate candidates for investment unless operators of commercial plants demonstrate readiness to scale up.

4.3 Recommendations

A. Pursue options and mechanisms to cut, rebate or guarantee lower energy prices to steelmakers and primary ironmakers in order to protect the UK steel supply chain as a whole

B. It is recommended to future proof UK primary iron capability by commissioning a detailed feasibility study be carried out for a single national hydrogen-ready NG DRI plant which can fully decarbonise the feedstock, act as some inertia on the grid (ie increase productivity during surplus renewable energy events) and integrate with ports, and domestic transport links to follow scrap routes to steelworks. Commission a feasibility study including maximum viable energy price, for a 2MT hydrogen ready DRI plant to be on stream by 2028. **Should the Steel Strategy be aiming for production levels above 'return to business as usual' then this is recommended as being of high importance and urgency.**

C. Explore a more phased capex and opex option for DRI via a comparative study on modular batch reduction options or integrated reduction and melting options delivering green pig iron substitute

D. Explore co-investment in international 'green iron corridor' assets

Both B and C should include realistic timelines to full green hydrogen operation.

E. Support R&D into EAF steelmaking with scrap and OBM blends based on UK supply as an issue of high importance and urgency. Maintain an active national R&D and innovation capability including close co-operation with Horizon Europe.

F. Consider and active accelerator programme for new ironmaking technology developments (ESF, plasma reduction, electrolysis and chemical routes as well as modular DRI)

G. Consider equitable transition / green steel 'contracts for difference' guarantees within the public procurement framework for steel products

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APPENDIX 1 – H2DRI STATE OF THE ART

(Internal MPI review, developed in 2022 H2DRI - IFS Phase 1 project; updated 2025)

The process of making direct reduced iron (DRI), a material with a fully reduced or more likely partially reduced metallic iron content is well established and has a growing market to exploit ore reserves with lower iron contents. Several proprietary processes have been developed worldwide, but all operate under essentially the same process conditions and thermodynamic constraints, utilising carbon-based gases (CO, CH_4), with hydrogen as a component, as the primary reductant of the iron ores. The two major furnace types for DRI production are the vertical shaft furnace (e.g., as used in the MIDREX process, Figure A1.1) and the fluidised bed furnace (e.g., as used in the FINEX process, Figure A1.2, and CIRCORED process, Figure A1.3). Plans have been made and, in some cases, implemented to modify the existing conventional DRI furnaces to use increasing hydrogen/natural gas ratios to reduce the use of carbon-based gas and mitigate CO_2 emissions.

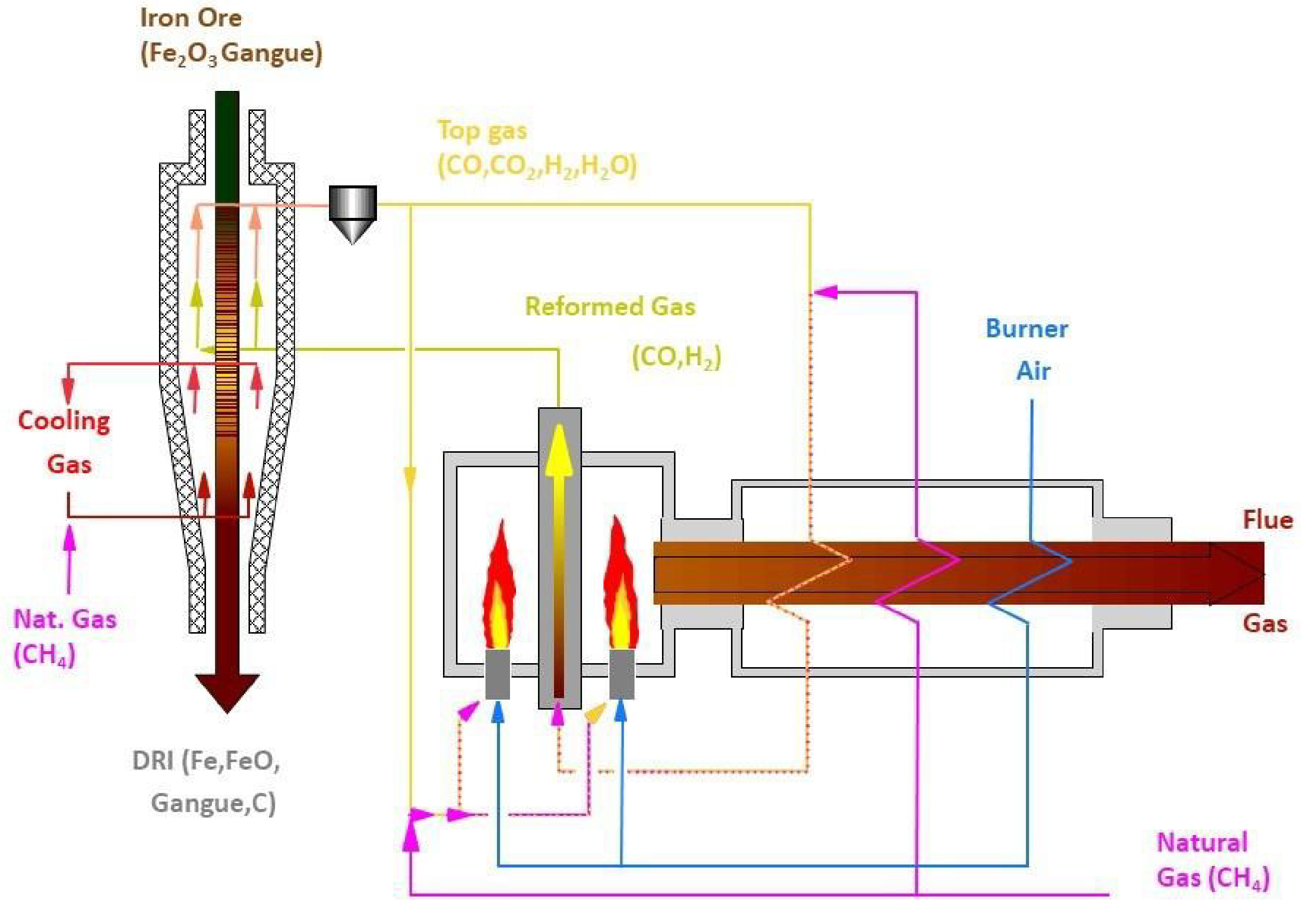

Fig. A1.1 Example of a shaft furnace DRI process: MIDREX

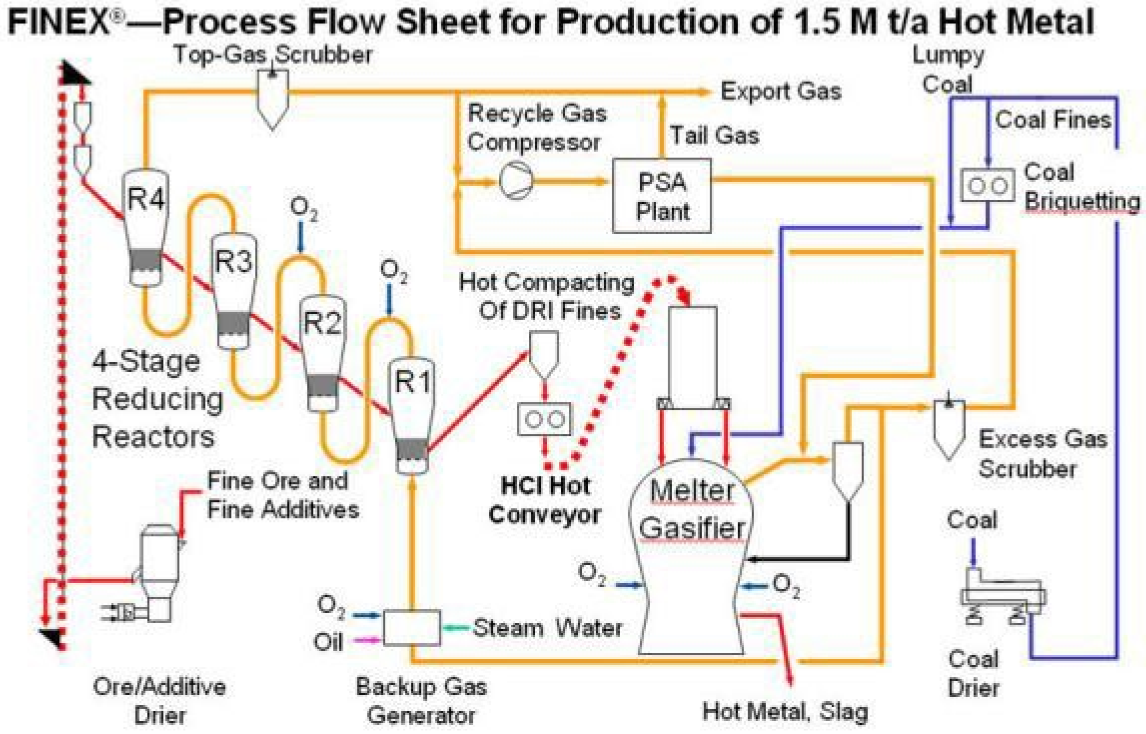

Fig. A1.2 Example of a fluidised bed DRI process: FINEX (Posco Pohang Works) as of 2006

Hydrogen-electric steelmaking has featured in multiple announcements by global steelmakers and OEMs since 2019 and yet proponents of hydrogen iron reduction must still address upstream and downstream implications on supply chains, plant and finished product since this is not a basic one-for-one fuel switch.

Fossil carbon supplies both reducing power and thermal energy in all commercial steelmaking processes:

1. Via coal/coke in Blast Furnace ironmaking (reducing and heating above 1200°C to melt the iron and allow slag separation)
2. Via natural gas or coal gas in Direct Reduction ironmaking (reducing and heating the solid product to 950°C)
3. Oxidation of excess dissolved carbon for heat in BOF steelmaking (heating molten iron to 1600°C)
4. A supplement in EAF steelmaking (adding heat to the electrically melted iron to maintain steelmaking temperatures of 1600°C and foaming the slag layer to protect electrodes).

Switching to hydrogen as the sole reductant also then implies electricity as the heat source for the endothermic solid reduction stage (to maintain reaction temperatures around 950°C), as in the 'HYBRIT' process [1], or simply blending increasing proportions of hydrogen as the reductant and capturing the remaining carbon emissions as in the Salzgitter AG and Tenova 'SALCOS' process [2].

Making hydrogen direct reduced iron (H2DRI) without dissolved carbon creates challenges for handling and steelmaking as it has the potential to be a pyrophoric product that lacks the dissolved carbon to aid later melting and refining. In common with commercial DRI it would most likely be briquetted for safe transport as hot briquetted iron (‘HBI’).

Since it remains solid throughout the reduction, H2DRI still contains any unwanted ‘gangue’ elements that were present in the ore, and they must be removed upon melting in the EAF with increasing expense and loss of iron content. This has reinforced the preference for high grade (high Fe content) ores in the current, conventional DRI markets.

Carbon content of H2DRI is therefore a prime topic, as is the question of which global ore deposits may or may not be economically viable for the H2DRI processes being developed, as the premium high iron-low gangue ore sources become exhausted. Ores that result in much greater slag volumes will require changes to EAF furnace designs and operators will need to market the slag products as well as the ‘green steel’.

These issues are well recognised within the steelmaking community and are drawn together in Hornby & Brooks’ 2021 paper, “Impact of Hydrogen DRI on EAF Steelmaking” [3]. Hornby’s 2016 paper, “Myths and realities of charging DRI/HBI in electric arc furnaces” [4], includes relevant analysis of the safety and economic aspects of carbon content in DRI products.

Recent publications, such as that by Vogl et al [5], assert that, “There is so far very little information on the hydrogen direct reduction (H-DR) process in the scientific literature.” By this they mean that, whilst there is an abundance of studies on the technicalities of the production of iron by direct reduction with hydrogen, there is little on how a potentially commercial scale, cost effective process design would operate or what its performance would be.

Innovative designs for potential H2DRI production are not new. Patents exist for processes to directly reduce iron ore using a CO/H_2 gas mix (30 % H_2) dating back to 1953 [6], using equipment that is closely related to the present study, albeit using the process gas for fuel and operating at temperatures high enough to melt the iron and gangue for separation in the reduction vessel.

To date, the only implementation of hydrogen in direct reduction on a commercial scale was in Trinidad. Conventional DRI was produced from 1999 onward in fluidised bed reactors using the CIRCORED process, with CO as the major reductant gas produced from natural gas combustion. The Improved CIRCORED facility of Mittal Steel Trinidad (Figure A1.3) [7] started production in 2004, with hydrogen generation from steam reforming to supplant the carbon-based gases. The plant was never a commercial success and was closed and mothballed in 2016 due to unsustainable levels of debt to the parent company. The plant was still closed and up for sale in 2021 and the current high gas prices will deter investment in the assets.

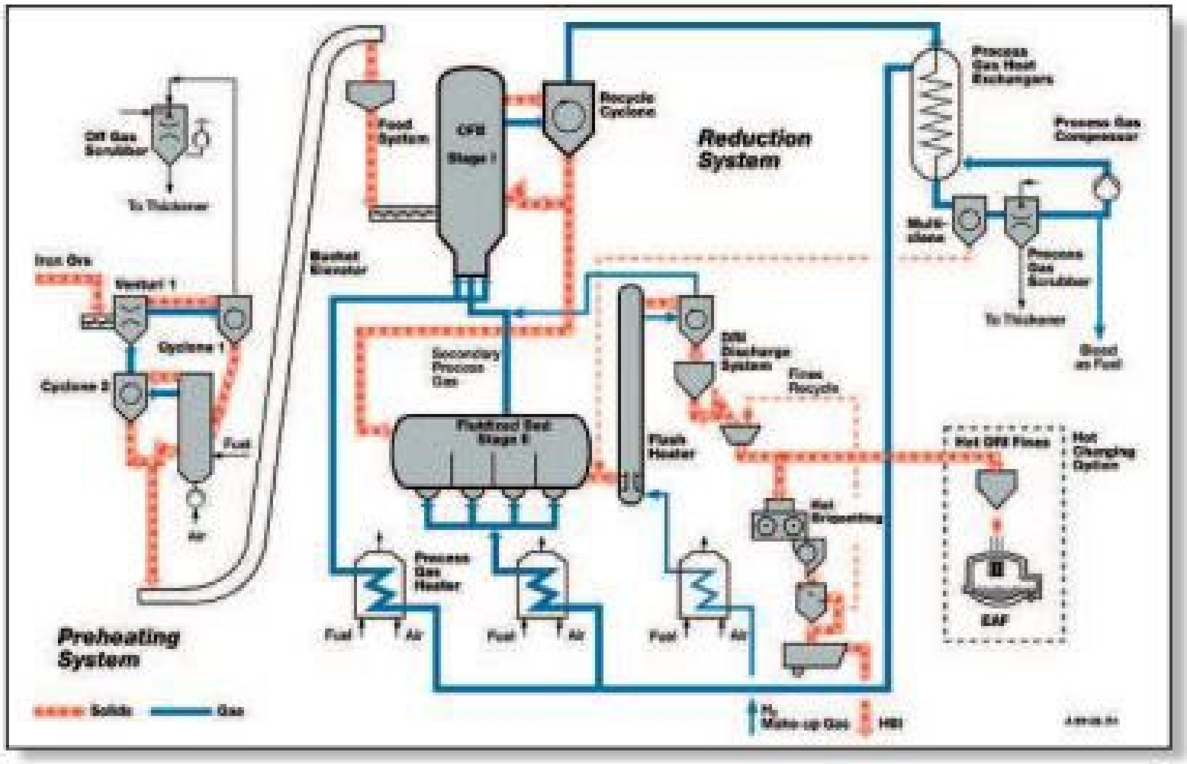

Fig. A1.3 Improved Circored Process Flow Sheet [7]

Several studies have investigated the potential for hydrogen direct reduction processes. Otto et al [8] used the Improved Circored process as a basis for their assessment of the emissions saving potential of direct reduction with hydrogen. However, it should be noted that as the hydrogen used in the Improved Circored process is generated from steam reformation, it cannot be considered as green technology. Multi-criteria analyses (including economy, safety, ecology, society and politics) were used by Fischedick et al [9] and Weigel et al [10]. Both studies identified hydrogen direct reduction as the most promising production route, compared with the electrowinning and blast furnace / basic oxygen furnace (BF/BOF) steelmaking routes, with and without the use of carbon capture and storage (CCS) to mitigate emissions. A novel approach was tried by Germeshuizen and Blom [11], who studied direct reduction with hydrogen that was produced in a hybrid sulphur process using nuclear process heat. They considered other options to reduce BF/BOF emissions, including hydrogen injection into the BF and top gas recycling. However, the maximum CO_2 emission reductions that they calculated amounted to 21% for hydrogen injection and 24% for top gas recycling, figures regarded as insufficient for deep decarbonisation.

A better understanding of existing hydrogen direct reduction technology, adapted from conventional carbon-based processes, and new technology entering the arena is important for developing viable decarbonisation pathways for the steel industry. Additionally, the integration of these processes into a fully decarbonised electricity supply chain must be included in the evaluation.

As mentioned above, a series of projects to produce ‘green steel’ have already started around the world. An overview of the key European projects that have kicked off since 2020 is given below.

Austria

In March 2018, the Austrian government approved a pilot hydrogen plant for voestalpine, the first stage of plans to implement hydrogen direct reduction, requiring an electrolysis plant for hydrogen production. voestalpine's aim is to produce carbon neutral steel by 2050 and is developing highly innovative technologies and production processes in a phased plan referred to as “greentec steel”. As part of its “sustainable steelmaking” (SuSteel) research project under this plan, the company is investigating the use of hydrogen plasma in a carbon neutral steel production process. A new pilot facility started operation in 2021 at the voestalpine site in Donawitz. voestalpine claim that it is currently the world's only steel manufacturer conducting research into the use of hydrogen plasma in steelmaking [12]. voestalpine have also publicised the granting of a European patent for carbon-neutral pre-material used in green steel production [13]. The patent specifically covers the production of sponge iron (DRI or HBI) using green hydrogen and biogas. However, searches of patent databases have not yielded any results to verify the claim.

Germany

Salzgitter, Linde and Avacon Natur are collaborating on the joint “Salzgitter Clean Hydrogen” innovation project. The aim is to generate hydrogen in Salzgitter through electrolysis and electricity from wind power for the deployment of larger hydrogen volumes required for the Salzgitter AG and Tenova ‘SALCOS’ process [2] to reduce direct CO_2 emissions in the production of steel. Hydrogen delivered by Linde is already being used at Salzgitter in the annealing processes that are part of producing steel. In addition, the use of hydrogen in the mills opens up the potential of significantly reducing CO_2 emissions generated from steel production processes in the future.

ArcelorMittal have commissioned Midrex Technologies to design a demonstration plant for hydrogen steel production in Hamburg. First announced in late 2019 and followed up in 2020 [14], this was the first announcement of modified MIDREX technology to achieve hydrogen direct reduction at a large scale under the ‘H2H’ project. The collaboration agreement covers cooperation on several projects, ranging from research and development to the implementation of new technologies. There are several project development agreements, the first of which is to demonstrate in Hamburg the large-scale production and use of DRI made with 100% hydrogen as the reductant. The demonstration plant will eventually produce about 100,000 tonnes of H2DRI per year, initially with grey hydrogen sourced from natural gas. Conversion to green hydrogen from renewable energy sources will take place once it is available in sufficient quantities and at an economic cost. ArcelorMittal claim the plant will be the world's first direct reduction plant on an industrial scale, powered by hydrogen.

Thyssenkrupp have developed a strategy for transition to carbon-free steelmaking, ‘blast furnace 2.0’ [15], with initial investigations of direct hydrogen injection into the tuyeres of the blast furnace and high levels of conventional DRI in the burden. Eventually, H2DRI will be used once sufficient quantities become available, alongside developing a process route for an integrated melting module beneath a H2DRI furnace, taking the output directly to replace the blast furnace process.

Sweden

The Swedish-owned ‘HYBRIT’ project [2] is the best publicised and furthest advanced of all the current pilots. Created in 2016 between minerals company LKAB, energy producer Vatenfall and steel producer SSAB, it aims to achieve commercial scale green steel production by 2035. ‘HYBRIT’ pilot project activities progressed steadily and in summer 2019, ‘HYBRIT’ started to build a pilot plant in Malmberget to do tests for production of fossil free pellets. In parallel, trials have been conducted in an experimental facility in Luleå, testing more alternatives, such as CO_2-free plasma and non-carbon fuels that have not yet been commercialised. A pilot project in Luleå supports storage of hydrogen required to operate the first pilot plant and SSAB demonstrated ‘fossil free’ reduction of premium Swedish iron ore by hydrogen at a tonnes per day scale (Technology Readiness Level 5) in 2021, with plans to start building a larger scale demonstrator in 2023.

It should be noted that ‘HYBRIT’ is the closest in overall concept to the H2DRI proposal, since:

1. It uses a pure hydrogen reducing gas
2. Introduces carbon separately via small amounts of biocarbon as binders in the ore pelletisation
3. Anticipates blending biocarbon with powdered coal for balancing carbon content of the final steel and energy use in the EAF once 100% H2DRI melts become established.

The paper by Vogl et al [5], provides some background to the ‘HYBRIT’ project and provides good economic comparisons (CAPEX and OPEX) versus the blast furnace / BOF route, based on Swedish data.

SSAB present a complete picture as to how they intend to offer ‘largely fossil free’ steel by about 2030. Involvement in the HYBRIT programme to produce low CO_2 steel through hydrogen reduction of ores has enabled them to be an early mover in the production of trial batches of low carbon steels. They have already launched brands for their low CO_2 products as SSAB Zero™ and SSAB Fossil-Free™ [16].

Stegra (formerly H2GreenSteel) are currently building a hydrogen reduced iron plant at Boden, Sweden. This is a greenfield site approximately 40km from the Baltic port of Luleå [17]. The plant will have the capacity to produce 2.1 million tonnes of iron per year. Some of the iron is anticipated to be used in the new steel plant being built at the same location and some will be hot briquetted for sale onto the open market as hydrogen direct reduced iron (H2DRI).

The iron reduction plant is using technology supplied by Midrex/Kobe Steel and hydrogen will be produced by a 700MW electrolyser supplier by Thyssen Krupp Nucera. Stegra have announced that they will start production in late 2025 and may be the first large scale H2DRI plant if production starts before that of the planned HYBRIT demonstration plant.

A new entrant to the European H2DRI market is Swedish startup GreenIron, based in Sandviken (160 km north of Stockholm), who have an alternative hydrogen DRI technology to the continuous shaft furnace, using pellet feedstock: a modular (5 tonne x 1 hour) batch process launched at commercial scale in 2024 based on a 5 tonne per hour (30,000 tonne per year) reactor module plus electrolyser and heat recovery [18]. The technology is scalable depending on hydrogen or grid electrical availability and growth of demand. GreenIron plan for 200 furnaces to be installed in the next 5 years claiming this would save the equivalent of 3% of Sweden’s CO_2 emissions. GreenIron are currently proposing a build and operate ‘green iron as a service’ model which is also capable of recycling (reducing) millscale and mine-tailing wastes. This technology is targeting the incremental (batch) use of H2DRI in a mixed scrap/H2DRI steelmaking process, with a controllable and variable power load linked to production levels. A feedstock change is in theory possible on an hourly basis to fine tune H2DRI chemistry and production can be cycled on or off within an hour. Although pelletised feedstock is used to maintain permeability in the reduction basket, the batch reactor does not require energy intensive ‘hot pellet’ (i.e. bonded at high temperature for strength) which is often necessary for conventional, natural gas DRI shaft reactors.

UK

Initiatives to replace the BF/BOF process for iron and steel production have been slow to proceed. British Steel previously published plans stating that their long-term strategy is to transform to electric steelmaking and plan to install new EAF facilities at Scunthorpe. No final decision on this change has been made at the time of writing. Tata Steel UK have closed their BF/BOF operations at Port Talbot and are proceeding with planning, design and installation of new EAF steelmaking facilities. The UK lacks any DRI production facilities, since the only two operational units sited at Hunterston (Figure A1.4), using local natural gas, were sold off and transported to Mobile, Alabama (Figure A1.5). One unit was then sold on to Saudi Arabia in the search for cheaper natural gas, while the other was mothballed.

Fig. A1.4 MIDREX Plant – Hunterston, Scotland

Fig. A1.5 MIDREX Plant – Mobile, Alabama

With a lack of conventional DRI production facilities to potentially convert to H2DRI operation, the UK must develop its own innovative technology to deliver the goal of sustainable, zero-carbon hydrogen-electric steelmaking and support Tata Steel UK, and potentially British Steel, if the strategically important steel industry is to survive. As outlined above, most major European steelmakers, and OEMs such as SEM, Danielli and MIDREX, are developing plans with similar approaches that are now entering the public domain. Production is planned to begin in the 2020s and investment announcements have been made in 2021 by voestalpine and ArcelorMittal, with confirmation of hydrogen-electric steelmaking as a medium horizon strategy by Tata Steel Europe in the Netherlands. Parent companies of these European steelmakers and OEMs in Japan, India and China are also considering the same strategies and are at varying stages of planning and implementation. The largest barrier to investment in the UK remains the energy price, whether for DRI production or EAF operation.

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APPENDIX 2 – OVERVIEW OF CC FOR BF

Carbon Capture for Blast Furnace Steelmaking – an overview of the current status

A comprehensive review of articles and technical papers about carbon capture (CC) technologies in blast furnace steelmaking was carried out by researchers from the University of Zaragoza, Spain, and Khalifa University, UAE [1]. This work presented the first systematic review of the integration of CC technologies in the blast furnace-basic oxygen furnace (BF/BOF) steelmaking route, which, at the end of the study in 2022, was expected to maintain a dominant market share over the coming decades. Integration options for post-combustion, looping cycles, oxy-combustion and pre-combustion were compared in terms of energy penalty, carbon emissions abatement potential, cost, technology readiness level, and practical deployment considerations.

The extensive review considered 188 studies from peer-reviewed articles and technical papers and analysed findings from 120 research articles. It was found that research was mainly focused on chemical absorption, physical adsorption, and oxy-blast furnace technologies. Other carbon capture methods, including calcium looping, Sorption Enhanced Water Gas Shift, and membrane technologies appeared promising in terms of cost and carbon emission reduction.

Where possible, the authors' analyses of published data and results were related to the overall operating envelope of an integrated steel plant, as illustrated in Figure A2.1.

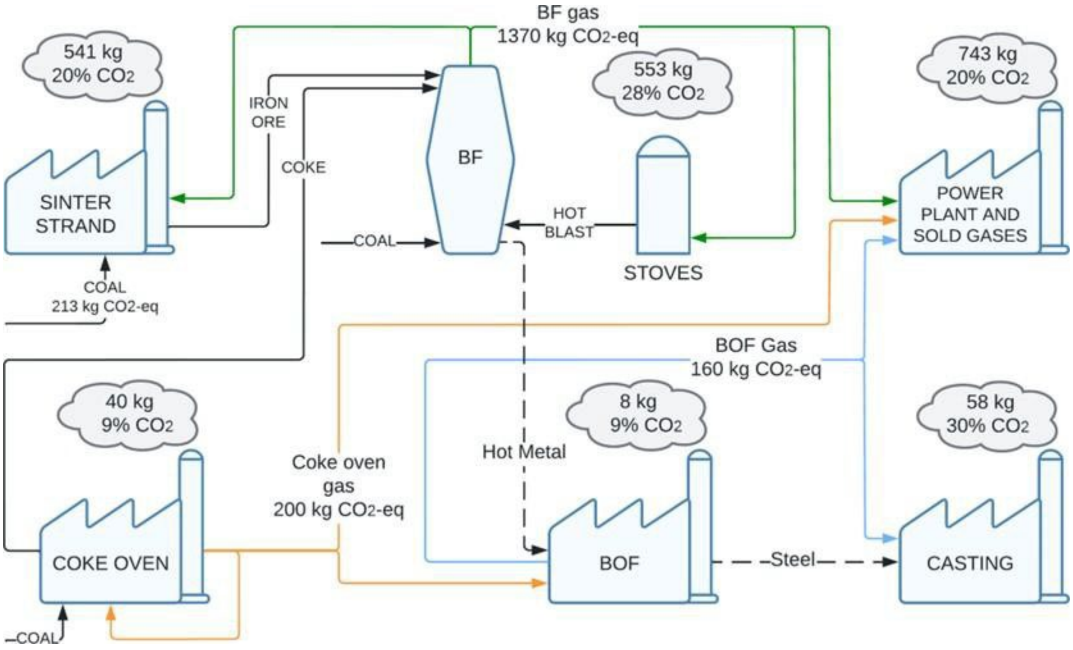

Fig. A2.1 Simplified flow sheet of an integrated steel plant, showing potential CO_2 emissions (kg/t steel) and concentration of CO_2 in flue gases (volume %)

Total emissions from the integrated steelworks from the sinter strand, coke ovens, blast furnace stoves, basic oxygen furnace, power plant and casting operations were directly correlated to the CO_2 equivalent emissions from the blast furnace, coke oven and BOF gases being used as fuels for the steelmaking processes.

Classification of carbon capture technologies

The authors classified CC technologies into four generic process routes, as shown in Figure A2.2, according to the technology applied in each category. These were further sub-divided into specific processes: chemical absorption, physical adsorption, membrane separation, calcium looping, chemical looping and Sorption Enhanced Water Gas Shift (SEWGS). When carbon capture was applied to gas streams with combustible species such as blast furnace gas (BFG), basic oxygen furnace gas (BOFG) or coke oven gas (COG), it was considered a pre-combustion system, while when applied to flue gases, it was designated a post-combustion system. No study related to pre-combustion CC systems was identified for the solid fuels employed in the iron and steel industry (i.e. coal and coke).

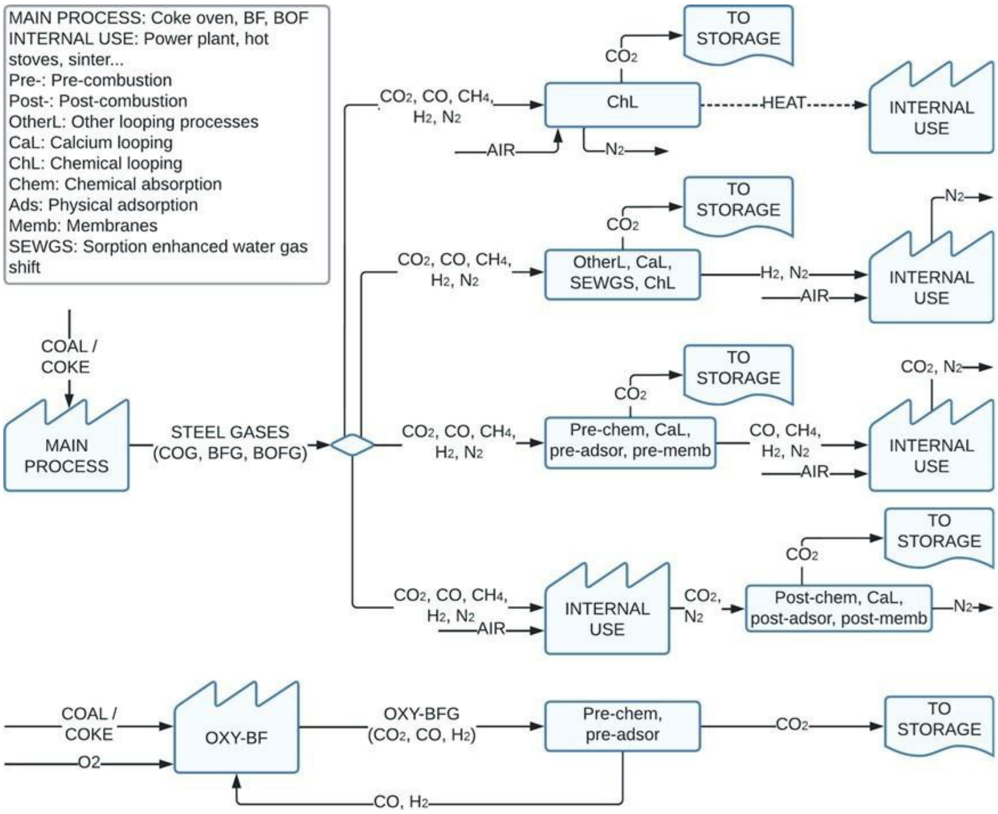

Fig. A2.2 Potential Carbon Capture routes in the Iron and Steel industry (BF/BOF route)

The only CO_2 capture process that is relatively mature (TRL 9) is that using amine solvents (Pre-chem). It is already commercialised in natural gas or fertilizer processing plants and was investigated at pilot-scale in the Oxy-Top Gas Recycling (nitrogen-free blast furnace) trials carried out on the LKAB experimental BF in Luleå for the ULCOS project [2]. However, no large-scale project was found in the literature regarding post-combustion capture with chemical absorption in the steelmaking industry. Perpinan et al believed this could be due to the large amounts of CO_2 to be processed, the high costs, and the geological storage difficulties [1]. They also found that most of the published works are theoretical studies and that where measured values were reported, emission reductions ranged between 11% and 77%, corresponding to 230 kgCO_2/tHM and 1700 kgCO_2/tHM, respectively.

Key Performance Indicators of carbon capture technologies

Following an in-depth review of each carbon capture (CC) technology, a detailed comparison of the technologies against six Key Performance Indicators (KPIs) was completed. The KPIs considered were: Thermal Penalty (MJ/kgCO_2), Electrical Penalty (MJ/kgCO_2), Cost (\$/tCO_2), CO_2 Emission Reduction (kg/tHM), CO_2 Purity (%) and Technology Readiness Level (TRL). Figure A2.3 shows the results of the KPI comparison. It should be noted that thermal penalties relate to the energy required for the chemical processes involved in CO_2 absorption, adsorption and desorption and electricity penalties relate to the electricity consumption required for CO_2 compression for transport and storage. Cost relates to the CAPEX and OPEX amounts for the CO_2 being processed.

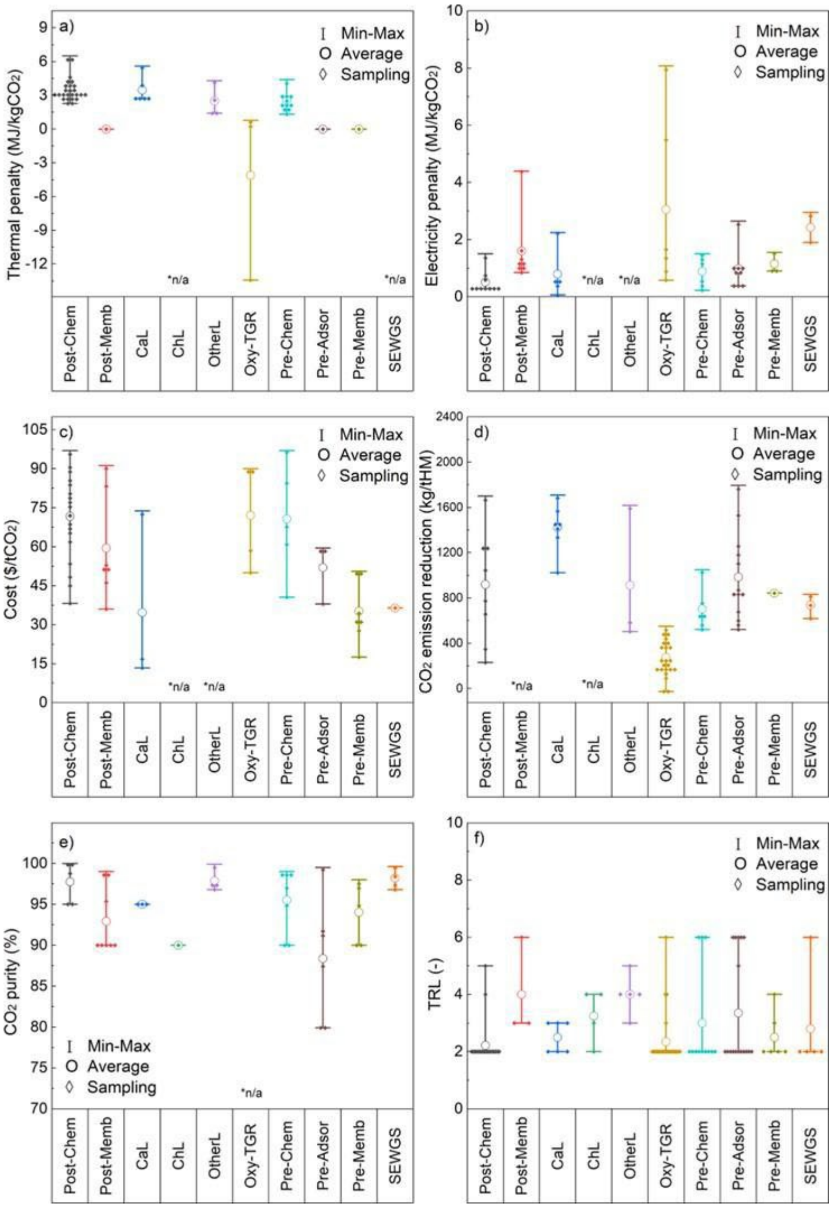

Fig. A2.3 Key Performance Indicator comparison for different carbon capture technologies: a) Thermal penalty (MJ/tHM), b) Electricity penalty (MJ/tHM) c) Cost (\$/tCO_2), d) CO_2 emission reduction (kg/tHM), e) CO_2 purity (%) and f) TRL (-)

Perpinan et al concluded that calcium looping (CaL), pre-combustion CC by adsorption (Pre-adsor) and post-combustion CC by chemical absorption (Post-chem) are the three technologies that have lower electricity penalty when capturing high amounts of CO_2, illustrated in Figure A2.4. CaL technology achieves the highest CO_2 emission reduction at a lower cost, but other technologies such as Post-chem, other looping processes (OtherL) and Pre-adsor achieve similar carbon capture rates, see Figure A2.5. Pre-combustion CC by membranes (Pre-memb) potentially has the lowest costs, but with lower CO_2 emission reduction potential at the date of the review (2022) and lower TRL (2-4).

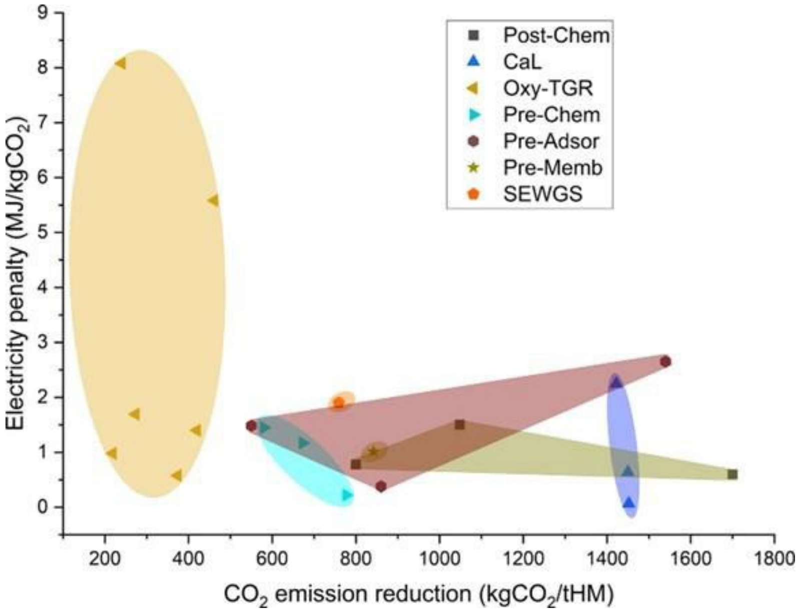

Fig. A2.4 Electricity penalty as a function of CO_2 emission reduction, by carbon capture technology

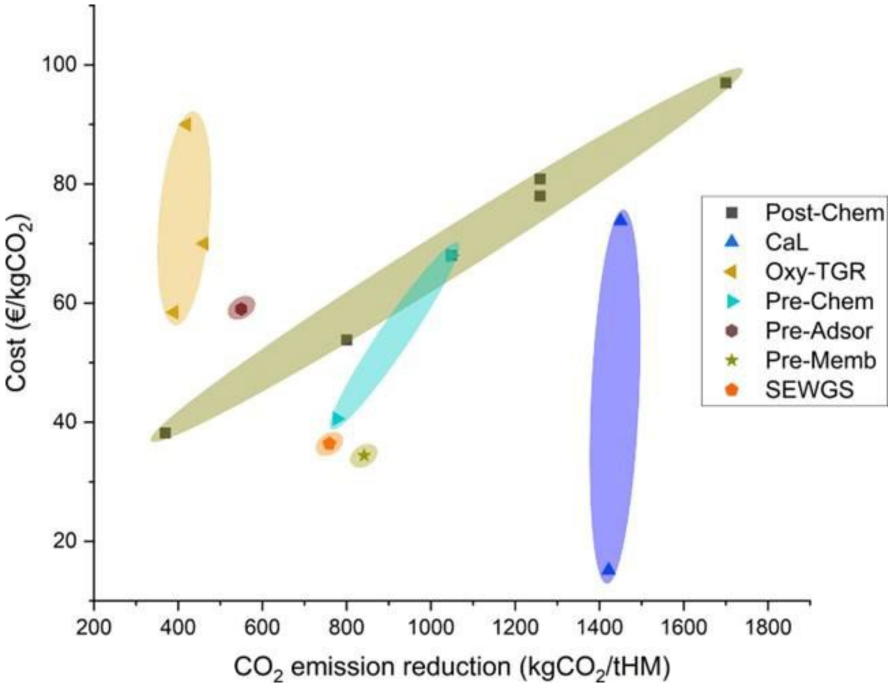

Fig. A2.5 Cost of CC as a function of CO_2 emission reduction, by carbon capture technology

CAPEX and OPEX requirements for CCUS

An Element Energy study [3] published in 2014 estimated capital costs for a CCUS retrofit plant (just below 35% CO_2 capture rate) at £294m with operational expenditure of £96m per year for a steelworks similar to the British Steel Scunthorpe plant. For higher capture rates, it was expected that capital costs would be significantly higher, especially if a rebuild of the blast furnace was required. Element Energy's figure will be significantly inflated over the last 10 years.

Estimates for cost per tonne of CO_2 captured vary depending on capture technologies and storage costs, but for retrofit of carbon capture technology, OPEX was estimated by ETI in 2016 to be around £65/tCO_2e, including transport and storage [4]. At the time, this would have led to an approximately 25% increase in the cost of producing a finished steel product, depending on product type and overall efficiency of the steel plant. This is a significant increase in the cost of steel products and immediately raises questions about how this cost would be recovered.

It is also worth mentioning the increased energy consumption related to CCUS operations at steel sites. An assessment by Budinis et al, in 2018, of CCUS in coal power generation [5] suggested energy penalties (i.e. the fraction of the output of the power plant that must be dedicated to CCUS activities) of 15-28%. In a scenario in which carbon capture was applied to power plants on ore-based steelmaking sites, it was estimated that a similar energy penalty would lead to a 10% increase in grid electricity cost and an additional OPEX cost of around £4 million a year (2018 prices) per site.

The lack of widespread deployment of CCUS at steel production sites is a key limitation, which has made feasibility, requirements, costs, and performance more difficult to assess. In addition to the requirements for capital investment and increased operational costs, some of the key barriers are:

- Increased operational complexity and risks,
- Plant integration risks,
- High levels of uncertainty regarding costs,
- Lack of staff familiarity and operating expertise,
- Availability of space onsite for CCUS plant,
- Health, safety and environment (HSE) considerations,
- Number of CO_2 streams per site,
- Budgeting.

Previously, location near to CCUS infrastructure has also been identified as a key enabler. If steel production is located close to CCUS infrastructure, it will enjoy a competitive advantage in terms of energy savings and lower costs compared to sites not located near CCUS infrastructure.

Latest opinion on worldwide CCUS developments

Simon Nicholas reports [6] that at the end of 2024 two major European steel producers were reviewing their already announced plans to shift to lower emissions technology. Their cause for concern is the continued high cost of green hydrogen production. However, the article goes on to warn that any steelmaker should think very carefully about adopting carbon capture and storage (CCS) as the solution for their current integrated steelmaking operations.

One of the producers, ArcelorMittal (Thyssenkrupp being the other), has confirmed that it was delaying final investment decisions across its portfolio of decarbonization projects, including a number of hydrogen-ready DRI plants planned to replace blast furnaces. Also, ArcelorMittal will probably revise down its 2030 emissions intensity targets, while remaining committed to all possible technologies for near-zero steelmaking. This includes carbon capture utilisation and storage (CCUS), although like green hydrogen, this technology is likely to only make a meaningful difference after 2030.

ArcelorMittal has one operational industrial-scale CCU facility and two pilot projects underway in Gent, Belgium. The industrial-scale CCU (carbon capture and utilisation) facility is the Steelanol project, which captures less than 2% of the Gent plant's annual CO_2 emissions. The very low capture rate demonstrates why steelmakers are turning to hydrogen-ready DRI instead of carbon capture.

According to Simon Nicholas, Agora Industry report that the 2030 pipeline of commercial-scale, low-carbon steel capacity is dominated by DRI projects totalling almost 100 Mt/yr. In stark contrast, commercial-scale CCS projects remain stuck on 1Mt/yr. It is expected that steelmaking via green hydrogen-based DRI will outcompete CCS on performance and cost.

CCS has a poor track record in all industrial sectors where it has been applied. For example, the Gorgon CCS project in Western Australia, which captures CO_2 mixed with extracted natural gas for storage underground, started injection in August 2019, 3½ years late. The plant gained approval on the condition that it injected 80% of captured CO_2 underground. However, performance to date has been well below this level and is getting worse. It has injected about 33% of captured CO_2, and the most recently released performance results, show this dropped further to 30%. Any captured CO_2 not injected is vented into the atmosphere. Not an acceptable or sustainable scenario.

Another poorly performing application of CCS is that of the oil and gas producer, Equinor, who have recently admitted that their flagship Sleipner CCS project had significantly over-reported carbon capture rates due to faulty monitoring equipment. This further highlights the risks that accompany carbon capture implementation. Often, low CO_2 capture rates go unmentioned.

The Al Reyadah CCS project, on a DRI-based steel plant in the United Arab Emirates, is the world's only operational CCS plant on a steelmaking operation. However, it only captures about 25% of the plant's overall emissions.

For the steel industry, CCS faces the same issues as other sectors, with the addition that in a fully integrated, coal/coke/sinter/blast furnace/basic oxygen furnace primary steelmaking operation there are multiple sources of carbon emissions to deal with (see Fig. A2.1). In addition, CCS at the steel plant does nothing to address the methane emissions from mining operations to win the coal used in the BF/BOF process route.

The scepticism of Simon Nicholas' article has been reflected by other organisations, such as E3G and Bellona, who have developed a CCS Ladder for Europe (Figure A2.6) showing that CCS for both blast furnace and DRI-based steelmaking will be costly and a "financial burden on the emitter". The Kleinman Center for Energy Policy at the University of Pennsylvania published a CCS ladder for industrial decarbonization in the US, which made similar findings. It is reported that both the International Energy Agency and Wood Mackenzie have reduced their expectations of steel CCS, lowering the amount of CO_2 they see being captured in the steel sector. Simon Nicholas believes that it is likely these expectations will continue to be lowered in the future.

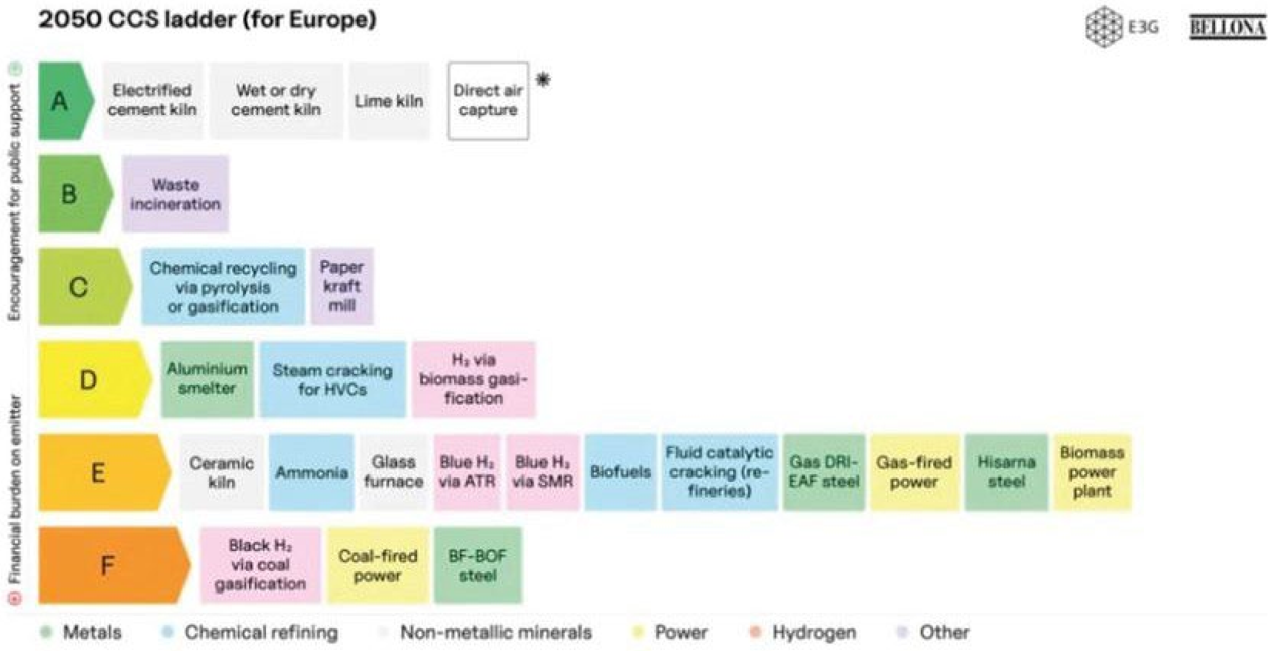

Fig. A2.6 E3G and Bellona – Europe CCS Ladder 2050

In November 2023, Transition Asia published a critique of the of the development of the green steel industry in Japan [7]. The big three steel producers, Nippon Steel, JFE Holdings and Kobe Steel have invested in a green steel strategy called COURSE50 that remains heavily reliant on the blast furnace – basic oxygen furnace route, with carbon capture. Transition Asia's view was that these steel companies would exceed their corporate carbon reduction budgets. Estimates quoted by Transition Asia put these at 821 MtCO_2 for Nippon Steel, 526 MtCO_2 for JFE and 137 MtCO_2 for Kobe Steel between 2019 and 2050.

The basis for the COURSE50 technology is injection of hydrogen, recovered from the blast furnace top gas, back into the furnace with the aim of replacing some injected coal and coke leading to a 10% reduction in carbon emissions. COURSE50 also relies upon CCS to reduce the aggregated carbon emissions across the integrated steelmaking sites. However, Transition Asia estimate that, "...emissions reduction effectiveness will be a maximum of 30%.".

COURSE50 has been under development since 2008 and is still not expected to be operational commercially until 2030 at the earliest. It remains unproven at scale and the evidence is that will be a high-cost technology. Transition Asia's conclusion is: "…the Big Three's announced plans and policies show that each surpasses their corporate 1.5 °C carbon budgets by substantial margins between 2019 and 2050. This is due to a heavy reliance on BF-based steel production; locking in emissions that are on track to exceed the carbon budget unless steps are taken to integrate largescale EAF into their steel production mixes. BF re-linings need to cease in the near future with plans to decommission these assets.".

With the UK steel producers already committing to replacing the BF/BOF, the role of CCUS to eliminate carbon emissions appears to be over. Adoption of CCUS could have been a stopgap to green steel production if it had been implemented earlier, when existing BF and BOF plants were younger and CAPEX requirements could have been rolled into the BF and BOF refurbishment programmes. Now, with only a single operational, aging BF/BOF primary steelmaking route in the UK, at British Steel in Scunthorpe, CCUS becomes a high risk, high-cost option that could be far too expensive to consider.

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2. ULCOS - Pilot testing of the low-CO_2 Blast Furnace process at the experimental BF in Lulea. G, Danloy et al. Rev. Met. Paris, 2009, Vol. 106.

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4. ETI. Progressing Development of the UK's Strategic Carbon Dioxide Storage Resource. ETI, 2016.

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6. S, Nicholas. Europe's green shift: carbon capture is not the answer. Steel Times International, January/February 2025, Vol. 49, pp. 36-39.

7. Transition Asia. Low Carbon Steel Development in Japan. Transition Asia, November 2023.

APPENDIX 3 – SELECTED REPRESENTATIVE DATA SHEETS

General Specifications for HBI (Ranges % by Weight) (based on 65.5 — 68.0% Fe Iron Ore)	
Metallization	94.0%
Fe (Total)	88.3 - 94.0%
Fe (Metallic)	83.0 - 88.4%
C	0.5 - 1.6%
S	0.001 - 0.03%
P_2O_5	0.005 - 0.09%
Gangue*	3.9 - 8.6%
Mn, Cu, Ni, Cr, Mo, Sn, Pb, Zn	Traces
Size (typical)	(90 - 140) x (48 - 58) x (32 - 34) mm
Fines & chips	≤ 5.0%
Apparent Density	> 5.0 t/m^3
Bulk Density	2.5 - 3.3 t/m^3
* residual unreduced oxides, mainly SiO_2 and Al_2O_3, but also CaO, MgO, MnO, etc.	
Source: IIMA Fact Sheet #2 (2017)	

General Specifications for DRI (Ranges % by Weight) (based on 65.5 — 68.0% Fe Iron Ore)	
Metallization	92.0 - 96.0%
Fe (Total)	86.1 - 93.5%
Fe (Metallic)	81.0 - 87.9%
C	1.0 - 4.5%
S	0.001 - 0.03%
P_2O_5	0.005 - 0.09%
Gangue*	3.9 - 8.4%
Size (typical)	4 - 20 mm
Apparent Density	3.4 – 3.6 t/m^3
Bulk Density	1.6 - 1.9 t/m^3
* residual unreduced oxides, mainly SiO_2 and Al_2O_3, but also CaO, MgO, MnO, etc.	
Source: IIMA Fact Sheet #11 (2018)	

Typical levels of residual elements in scrap and DRI/HBI

	%Cu	%Sn	%Ni	%Cr	%Mo	%Mn	%S	%P	%Si
No. 1 Bundles	0.07	0.008	0.03	0.04	0.008	0.03	0.02	0.01	0.005
Shredded	0.22	0.03	0.11	0.18	0.02	0.4	0.04	0.025	0.01
No.1 1 HMS	0.25	0.025	0.09	0.1	0.03	0.3	0.4	0.02	0.01
No. 2 Bundles	0.5	0.1	0.1	0.18	0.03	0.3	0.09	0.03	0.01
No. 2 HMS	0.55	0.042	0.2	0.18	0.04	0.3	0.07	0.03	0.01
DRI/HBI	0.002	trace	0.009	0.003	trace	0.06-0.10	0.002-0.007	0.03-0.07*	*

Source: IIMA Fact Sheet #11 (2018)

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[1] Establishment of technology to reduce CO2 emissions in blast furnaces using hydrogen Achieved world's first 43% reduction in CO2 emissions in a test furnace, reaching the development goal ahead of schedule https://www.nipponsteel.com/en/news/20241220_100.html

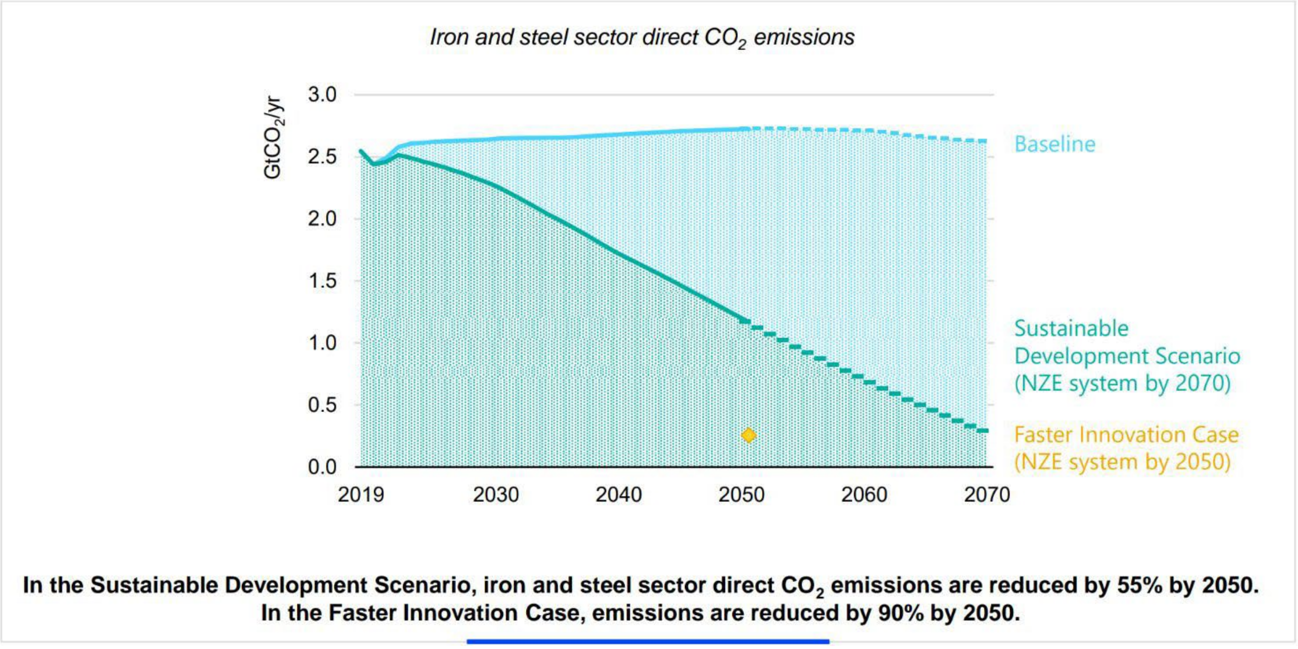
APPENDIX 4 – SELECTED “GREEN STEEL” CLASSIFICATIONS

Although ‘Green Steel’ is becoming a recognised catch-all term for steel products claiming or delivering significantly lower net emissions and other environmental impacts than the current average, there is no single universal standard for defining it.

This Primary Steelmaking Review has indicated the general ‘green steel’ thresholds for net CO2 emissions most likely to be relevant to UK steelmakers, based on current market understanding.

The foundational framework is the science-based approach to meeting the Paris Agreement as set out in the (2020) International Energy Agency (IEA) Iron & Steel Technology Roadmap (36) which envisages various scenarios emerging from the 2019 global baseline; and the follow-up IEA report (2022), Achieving Net Zero Heavy Industry Sectors in G7 Members (37)

Sustainable steelmaking requires deep CO_2 emission reductions



In the Sustainable Development Scenario, iron and steel sector direct CO_2 emissions are reduced by 55% by 2050. In the Faster Innovation Case, emissions are reduced by 90% by 2050.

Multiple Green Steel standards or definitions

There are currently at least 40 active standards or proprietary definitions in circulation, and several national or regional methodologies for measuring CO2 emissions for emissions trading or taxation purposes (for example EUTS, UK ETS, Indian ETS, CBAM) as well as international standards for industrial site environmental monitoring (ISO 140001) and energy management systems (ISO 40001, 50001) which define measurement and reporting frameworks.

Some of the most prominent systems for Green Steel definition are outlined below. There is a reasonable degree of compatibility between them, despite differences in methodology, philosophy and boundary definitions.

ResponsibleSteel

A voluntary standard which is currently the only international standard in the market. Includes net CO2 emissions factors per tonne of crude steel which recognise the but extends the definition of 'responsible' steel into a comprehensive framework. Issues certification with 4 'progress levels' ranging from 1 (signed up to the Standard for reporting but still at a high environmental impact in terms of operations) through to 4 (near zero impact)

The ResponsibleSteel International Production Standard V2.1 (38) states that the Standard "*consists of 13 Principles containing over 500 requirements for the responsible sourcing and production of steel, including some of the most challenging areas of sustainability for steelmakers such as decarbonisation. However responsible steelmaking goes beyond climate change mitigation. That's why the Standard also lays out requirements on labour, human rights, water, biodiversity, and more. We review the Standard at least every five years with the support and input of our members and stakeholders to ensure we continue to drive progress and promote the highest levels of responsibility for steelmaking*"

Within the Standard, Principle 10 addresses CO2 emissions factors, defining the system boundaries for steelmaking, and setting a threshold equation for each of the 4 Progress Levels based on the proportion of primary iron to scrap, combined with embodied CO2 of primary iron inputs and best practice in scrap melting

ResponsibleSteel are developing a guide to show equivalence with other standards, e.g. their (1-4 scale) level 4 is based on the (1-5 scale) IEA Near Zero level

SteelZero

SteelZero (39) is a demand-side initiative, and a partner to ResponsibleSteel - led by Climate Group with the aim of speeding up the transition to a net zero steel industry. Organisations that join SteelZero make a commitment to procuring, specifying or stocking 100% of their steel requirement by 2050 as net zero steel, with an interim commitment to procure, specify or stock lower emission steel for 50% of their steel requirement by 2030. This interim commitment can be met through one or both of the following pathways:

- Steel produced by a steelmaking site where the steelmaker has a science-based emissions target.
- 'Lower emission steel' (aligning with ResponsibleSteel Decarbonisation **Progress Level 2**)

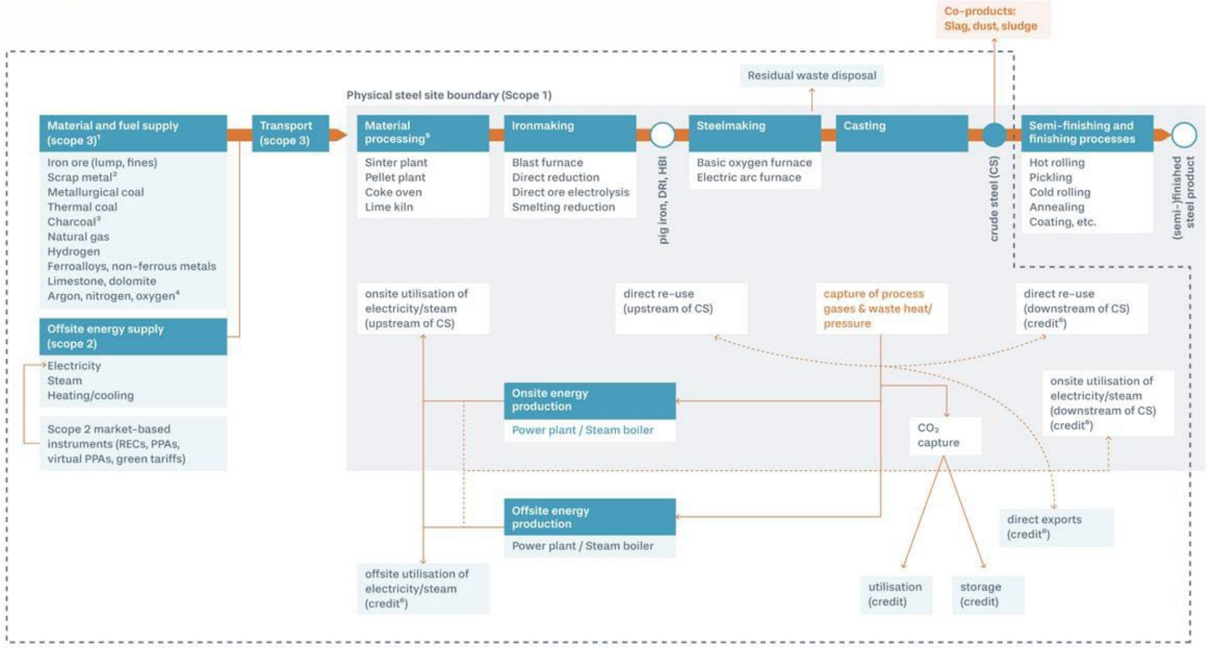


Figure 3– ResponsibleSteel's Emissions Boundary (under criterion 10.4) for Representation Iron and Steelmaking Sites

For illustrative purposes only – not all processes are shown.

1. For the full list of scope 3 requirements, refer to Annex 10 of the standard. For any non-listed items (e.g., graphite electrodes and refractories), if they are likely to contribute more than 5% of the scope 3 emissions they must also be included. The emissions boundary for each input is determined by materiality in accordance with recognised international standards. Refer to Criterion 10.4.5 for further details.
2. Upstream embodied GHG emissions for scrap metal are counted as zero, but emissions for transportation are included.
3. CO_2 sequestration associated with production of biomass-based products can be claimed when this is independently verified using a recognised standard. In the absence of independently verified primary data the emissions associated with the growth, harvesting and processing of biological materials are assigned a default net upstream GHG emissions factor of zero.
4. Oxygen plant is often located onsite for a BF-BOF plant.
5. Material processing can also be carried out offsite, with imports of iron ore sinter, iron ore pellets, coke and/or lime.
6. Credit given if re-used processes gases/generated electricity is greater than consumed gases/electricity upstream of crude steel.

Figure A4.1: ResponsibleSteel site boundary definitions

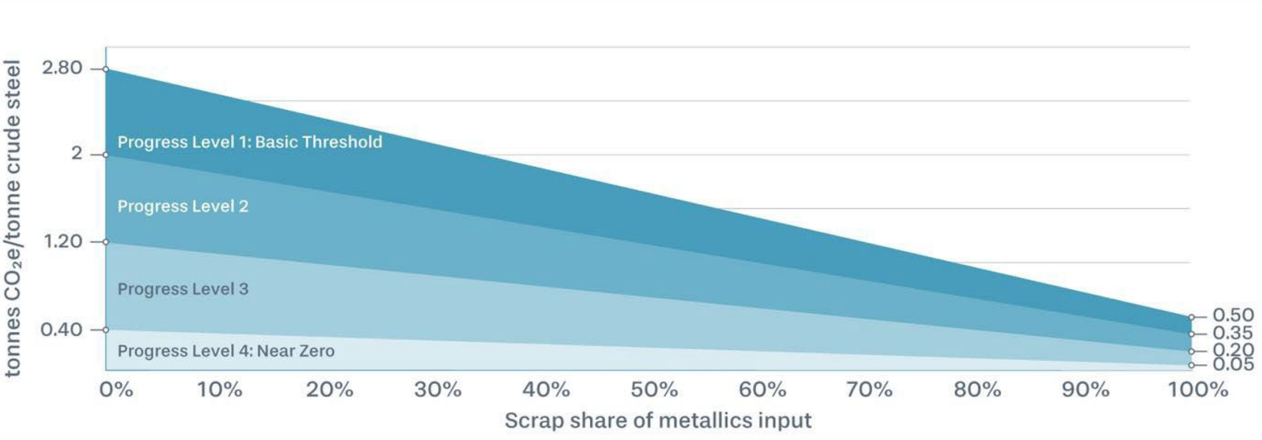


Figure 6 – ResponsibleSteel Decarbonisation Progress Levels

Figure A4.2: ResponsibleSteel Decarbonisation Progress Levels depending on scrap:metallics ratios

Global Steel Climate Council (GSCC) - Steel Climate Standard

Sets science-based targets and in 2024 published THE STEEL CLIMATE STANDARD Framework for Steel Product Certification and Corporate Science-Based Emissions Targets (40) from which the following descriptions and figures are taken

The Standard *“measures and reports steel carbon emissions. The framework aims to reduce GHG emissions across the global steel industry, is aligned with a science-based glide path to achieve a 1.5° C scenario by 2050 and requires third-party verification of emissions data and science-based targets.”*

The Glide Path approach is shown in Fig A4.3 below, and differentiates its limits for meeting the standard between long and flat products, recognising the different process challenges. In all cases, science-based emissions targets (SBET’s) are required: “as a first step in the target setting process, a company shall calculate the base year Company Average Steel Emissions Intensity (CASEI) for its steelmaking operations expressed as t CO_2e/t hot rolled steel”

Companies who have invested in decarbonisation and whose CASEI is already ahead of (i.e. below) the global glide path limits are required to set their own maximum limits path at a defined decarbonisation rate which stays ahead of the standard for some years but eventually converges. Companies with higher than glidepath CASEI must embark on a steeper trajectory and converge by 2040.

The standard is site specific, and also allows individual products to be certified using an LCA approach, for example if a steelmaker wishes to certify the use of low-emissions inputs (renewable energy, low emission OBMs, high scrap content) when making a particular physical product .

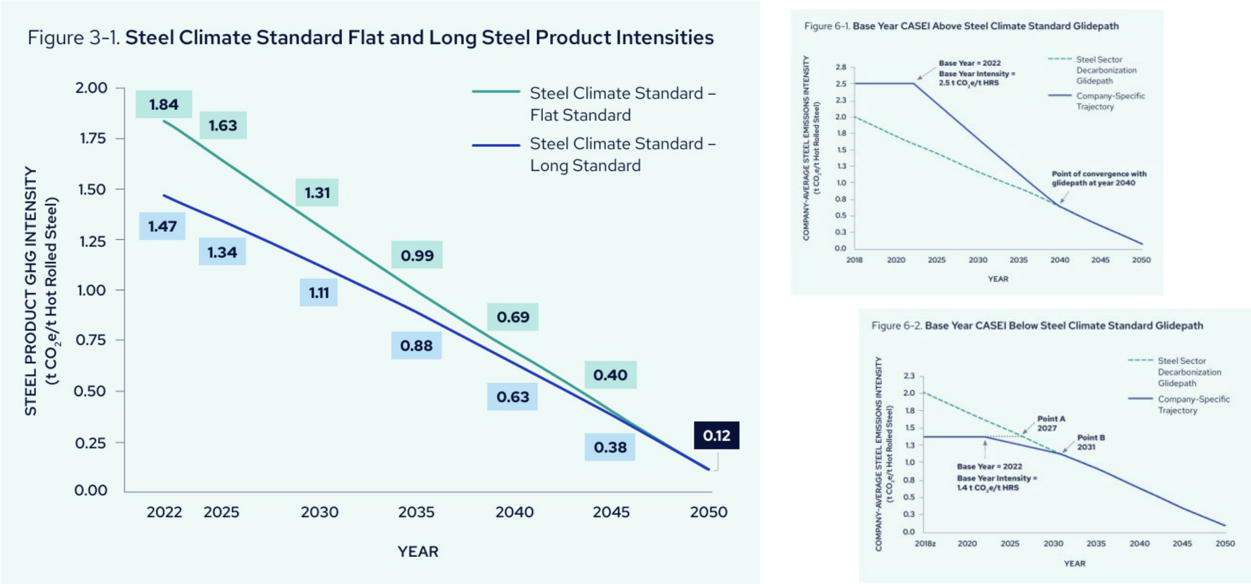


Figure 3-1. **Steel Climate Standard Flat and Long Steel Product Intensities**

Figure 6-1. **Base Year CASEI Above Steel Climate Standard Glidepath**

Figure 6-2. **Base Year CASEI Below Steel Climate Standard Glidepath**

Figure A4.3 – GSCC glidepath and requirements for convergence

LESS (Lower Emissions Steel Standard)

A standard developed by the German Steel sector, based on IEA and similar work , based on existing practices and with a site-specific mass balance approach[12]. The example in Fig A4.5 below applies the 5-step standard to a generic 'Quality Steel' made with 50% recycled scrap:

LESS is likely to grow in prominence within the EU over the coming years as it is promoted as a defacto European standard

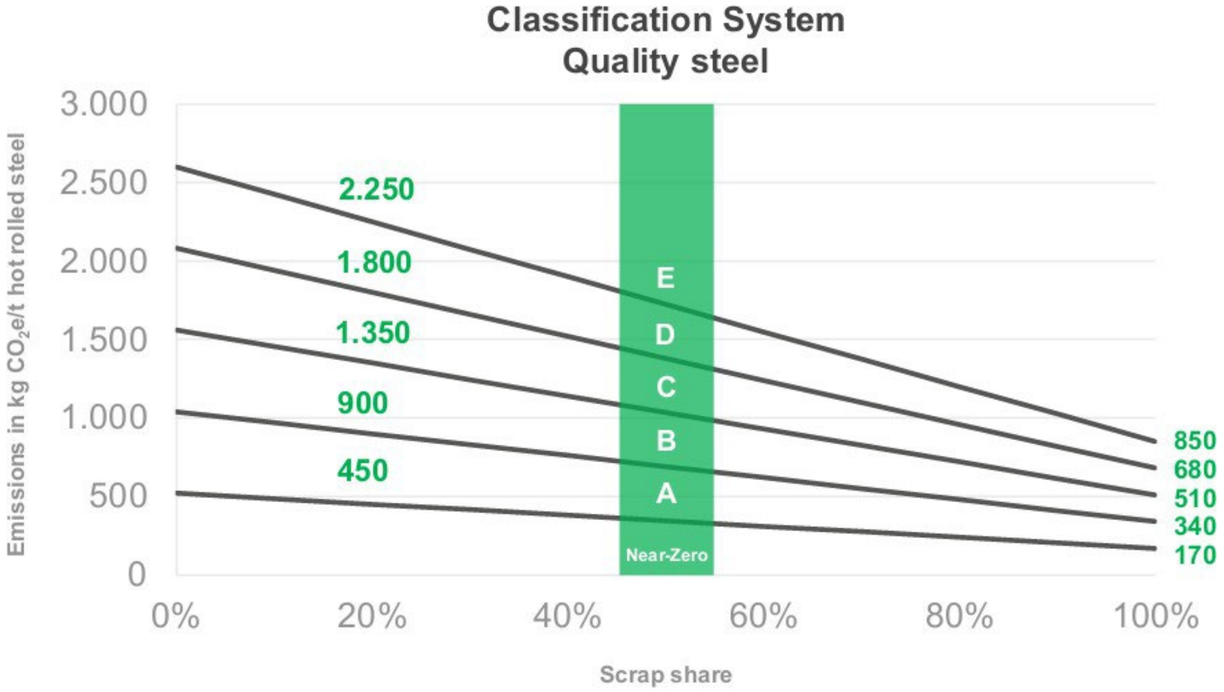


Figure A4.5 – LESS classification system overview including the example of 'Quality Steel'

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[1] https://www.wvstahl.de/wp-content/uploads/20240422_concept-paper_LESS_final.pdf

[2] https://www.wvstahl.de/wp-content/uploads/20240422_Rulebook_Classification-System-for-LESS_v1.0.pdf

Taxonomy of Green Steel for India

The Ministry of Steel in India released the world's first national taxonomy for green steel (3) as a mandatory pathway to achieve an emission intensity of **2.2 tCO2 per tonne by 2030**, and net zero by 2070.

The salient features of green steel taxonomy –

1. **"Green Steel"** shall be defined in terms of percentage greenness of the steel, which is produced from the steel plant with CO_2 equivalent emission intensity less than 2.2 tonnes of CO_2e per tonne of finished steel (tfs). **The greenness of the steel shall be expressed as a percentage, based on how much the steel plant's emission intensity is lower compared to the 2.2 t-CO_2e/tfs threshold**.

2. Based on the greenness, the Green steel shall be rated as follows:

- **Five-star green-rated steel**: Steel with emission intensity lower than 1.6 t-CO2e/tfs.
- **Four-star green-rated steel**: Steel with emission intensity between 1.6 and 2.0 t-CO2e/tfs.
- **Three-star green-rated steel**: Steel with emission intensity between 2.0 and 2.2 t-CO2e/tfs.

Steel with emission intensity higher than 2.2 t-CO2e/tfs shall not be eligible for green rating.

3. The threshold limit for defining the star rating of Green Steel shall be reviewed every three years.

4. The scope of emissions shall include Scope 1, Scope 2, and limited Scope 3, up to finished steel production. Scope 3 emissions shall include agglomeration (including sintering, pellet making, coke making), beneficiation, and embodied emissions in purchased raw materials and intermediary products, but shall not include upstream mining, downstream emissions and transportation emissions, both within and outside the gates of a steel plant.

5. The National Institute of Secondary Steel Technology (NISST) shall serve as the nodal agency for measurement, reporting, and verification (MRV) as well as for issuing the greenness certificates and star ratings for the steel.

6. The certificate shall be issued on yearly basis (financial year). In case the steel plants opt for MRV more frequently, then the certificate may be issued more than once in a year as per the requirement.

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